Realism of cloud structures in LES and its use for cloud and radiation parameterizations

Pier Siebesma (siebesma@knmi.nl)
Stephan de Roode (roode@knmi.nl)
Alexander. Los (los@knmi.nl)
KNMI, De Bilt, The Netherlands.

Harm J. Jonker (h.jonker@ws.tn.tudelft)
Technical University Delft, The Netherlands

Roel Neggers (neggers@ecmwf.int)
ECMWF, Reading, UK

For details see: Siebesma and Jonker: Phys Rev Let. 85 p214 2000

Neggers et al: JAS 60 p1060 2003

De Roode et al: JAS 61 p403 2004

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Climate Model Development strategy

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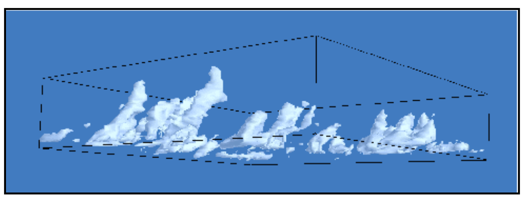
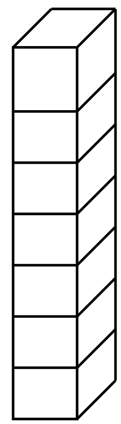
- Topics: turbulence, clouds, convection,radiation
- Methodology:

DALES

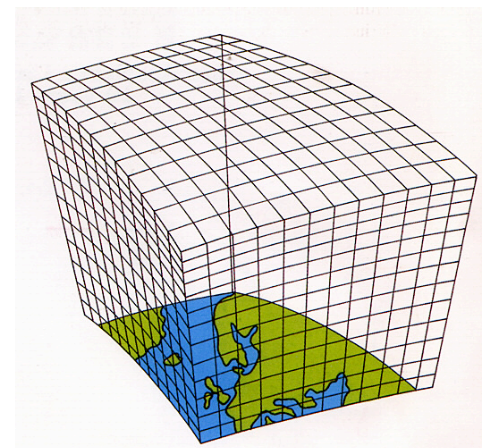


Large Eddy Simulation Models

+ Observations



Single Column Model version



3d RACMO-2

= “limited area version of ECMWF-model”

- Internationally embedded in: GEWEX Cloud System Systems (GCSS) (www.gewex.org/gcss.html)

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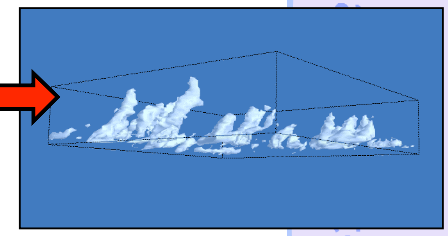
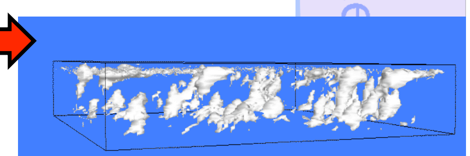
GCSS (WG1) bl-clouds Cases:

Type	Case	Parameterization Issues adressed:
Nocturnal Scu	FIRE (1987)	Top-entrainment
Shallow Cu (steady state)	BOMEX (1969)	Mass flux, cloud cover, lateral entrainment
Shallow Cu topped with Scu	ATEX (1971)	Mass flux, cloud cover, lateral and top entrainment
Shallow Cu (Diurnal Cycle)	ARM (June 21, 1997)	Mass flux, cloud cover, lateral entrainment
Scu (Diurnal Cycle)	FIRE (1987)	Top-entrainment, Radiation
Scu (precipitating)	DYCOMS (2001)	Top-entrainment, Radiation, Precipitation





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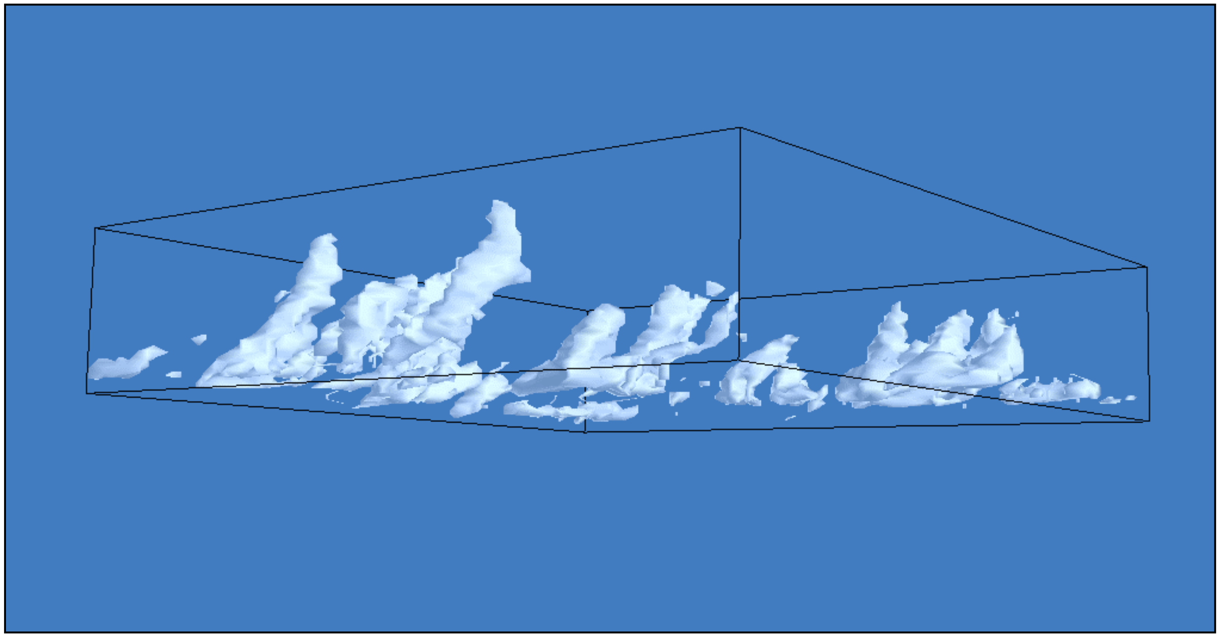
•••• LES widely used within GCSS to study turbulent transport in Cloud topped PBL



But…………

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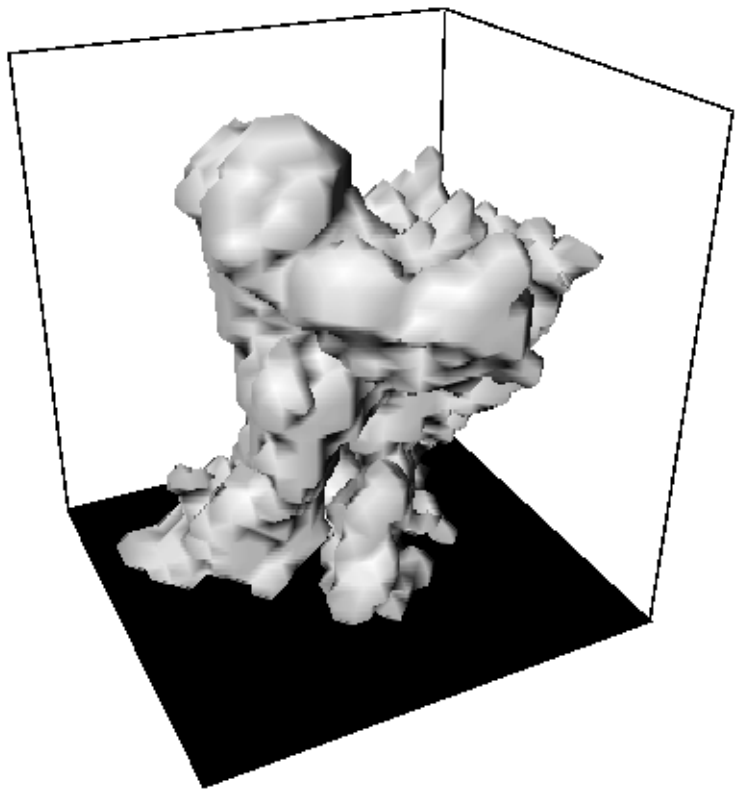
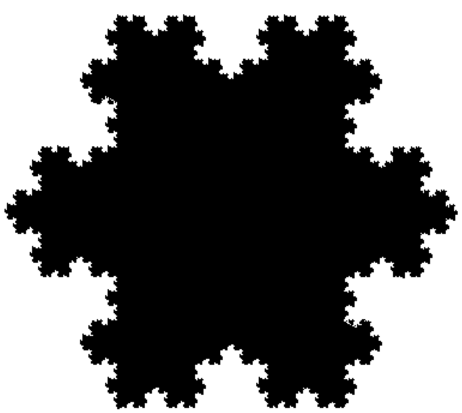
3. **Is this a Cloud??**



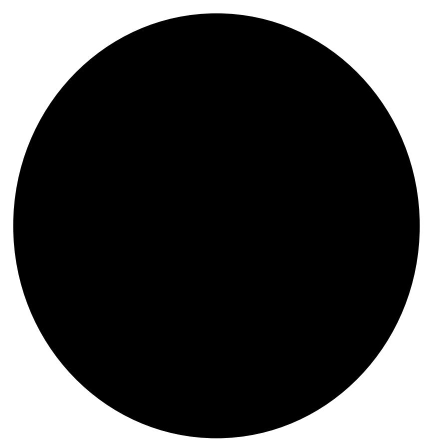
How to answer this question?

Area-Perimeter analyses of cloud patterns

- Pioneered by Lovejoy (1981)
- Area-perimeter analyses using satellite and radar data
- Suggest a perimeter dimension Dp=4/3 of projected clouds



Instead of



•••• 4. Similar analysis with LES clouds

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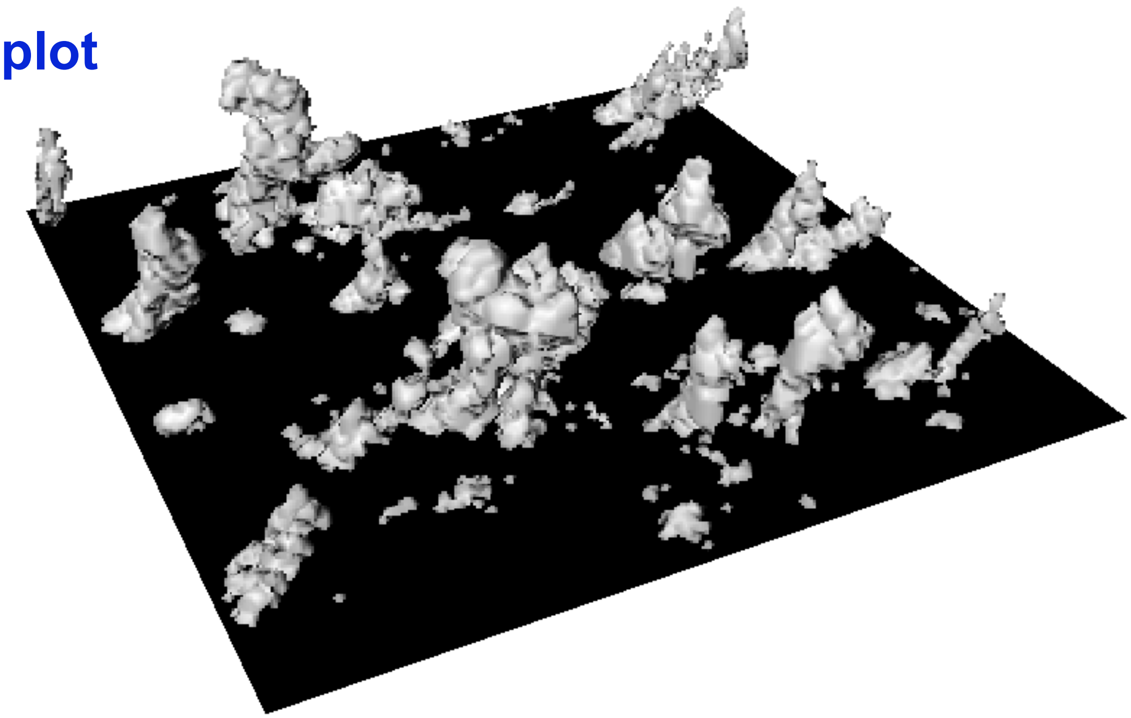
•Measure Surface A_s and linear size $l \cong V^{1/3}$ of each cloud

•Plot in a log-log plot

• $A_s \propto l^{D_s}$



•Assuming isotropy, observations would suggest Ds=Dp+1=7/3

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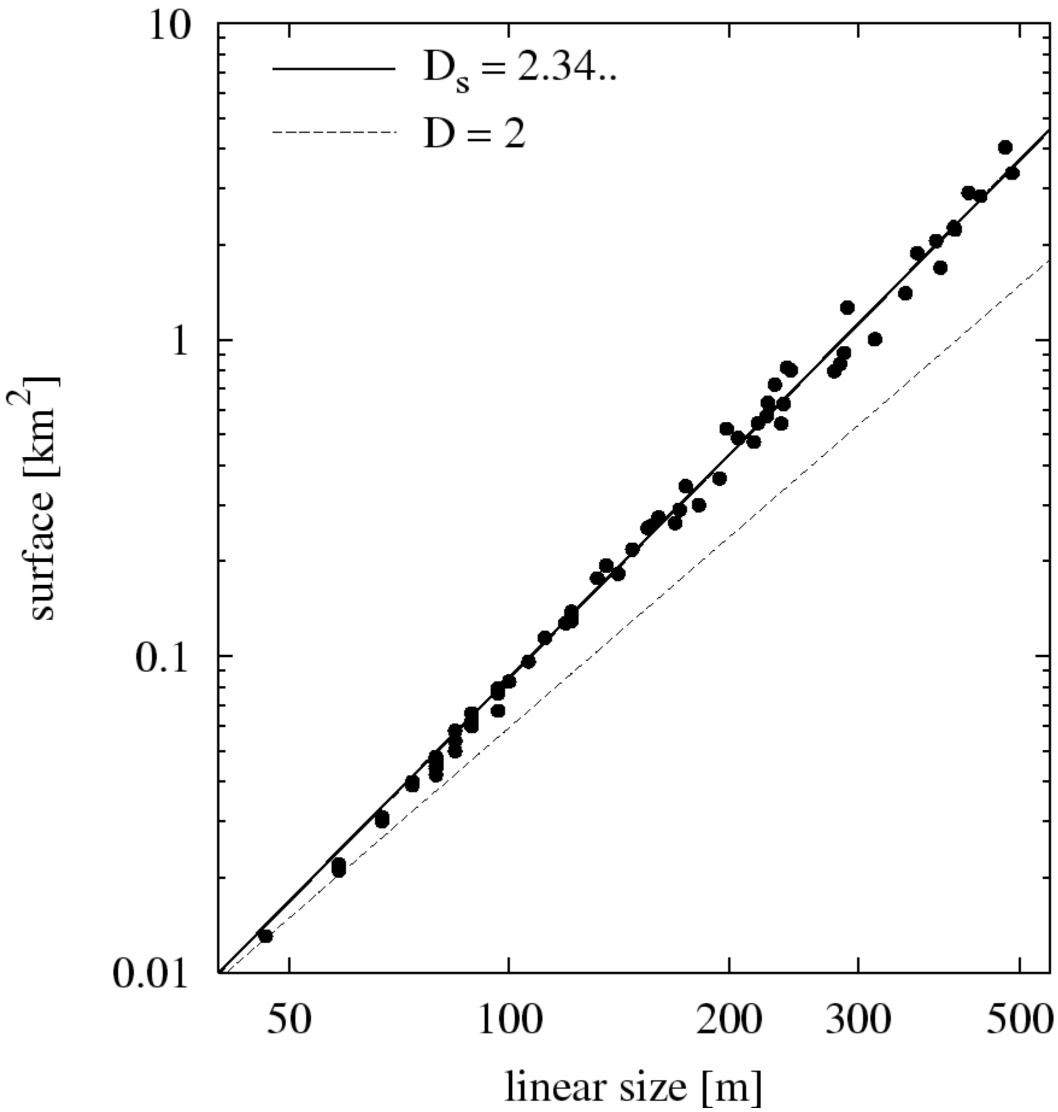
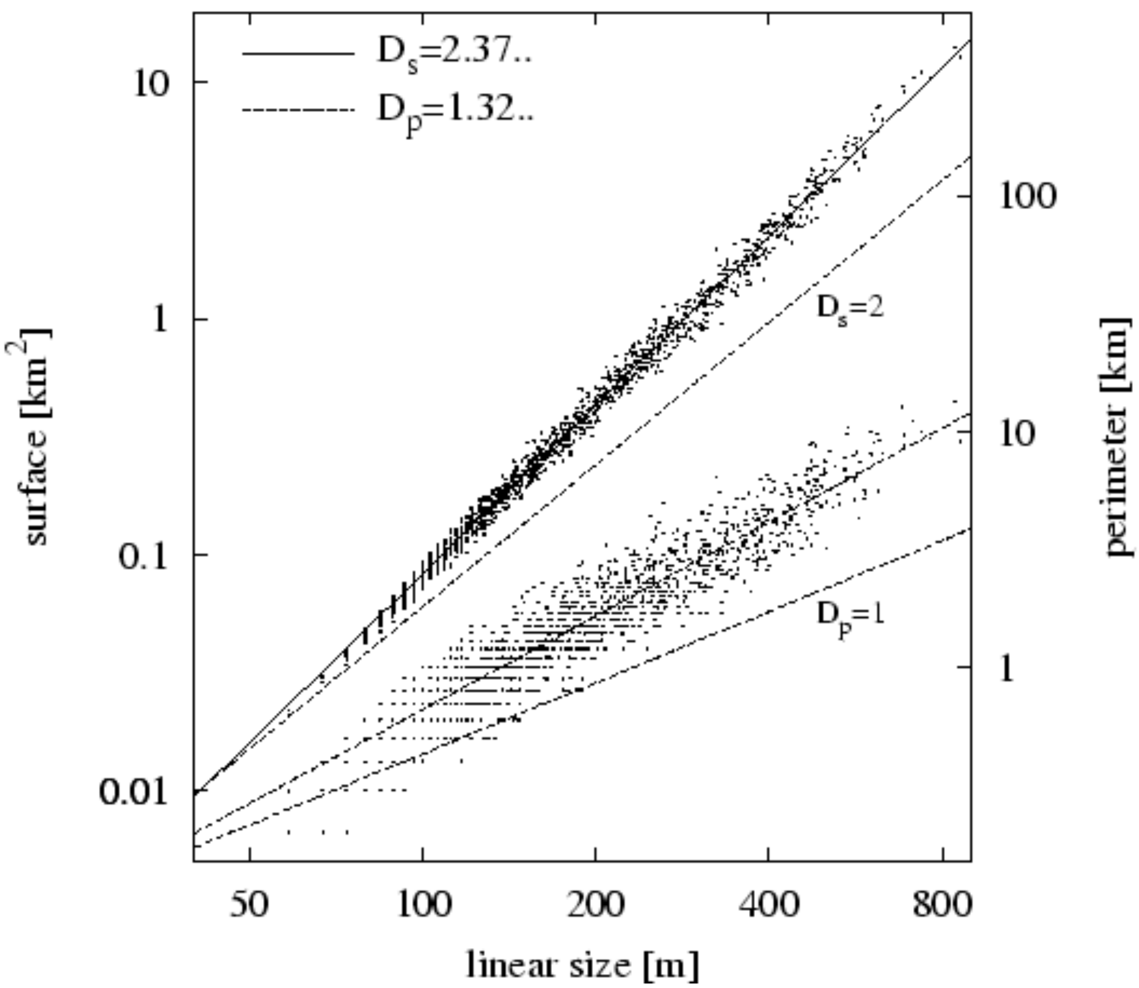
5. Result of one cloud field



Repeat over 6000 clouds



7. Consequences

- Surface area can be written as a function of resolution l:

$$S(l) = S_L \left(\frac{l}{L} \right)^{2-D_s} \qquad with\ D_s \cong 7/3$$

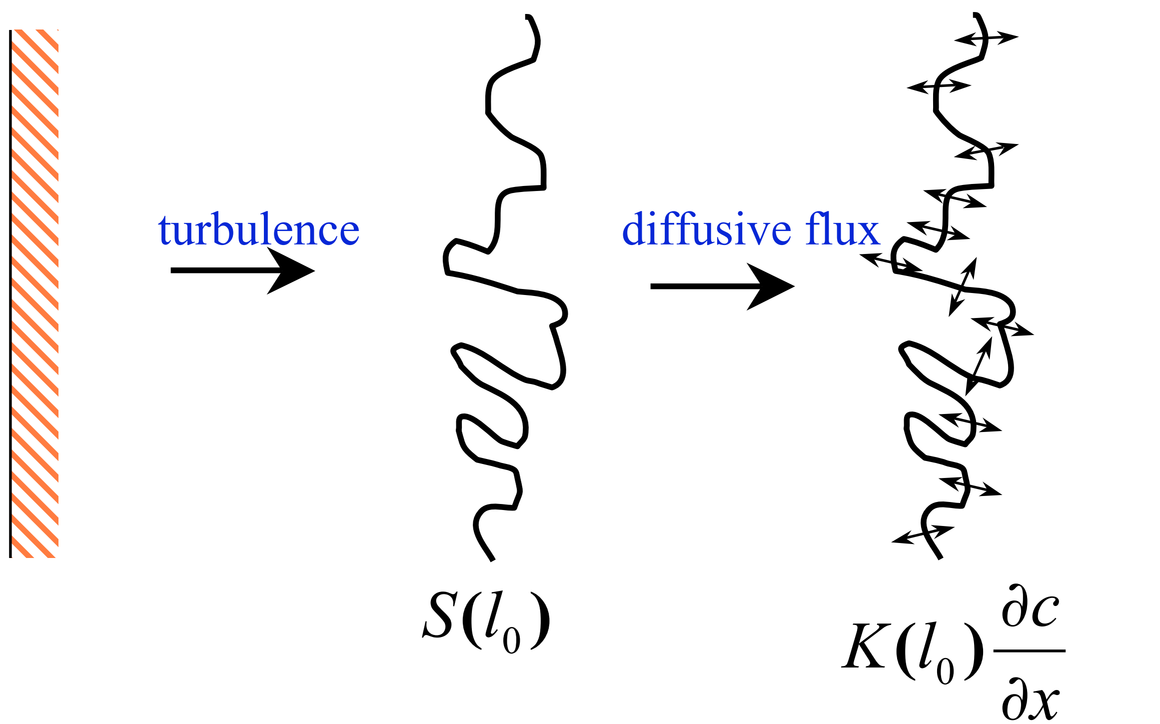
- Euclidian area SL underestimates true cloud surface area S(l=h) by a factor $(\eta/L)^{2-D_s} \approx 100$

- LES model resolution of l=50m underestimates cloud surface area still by a factor 5!

8. Resolution dependence l_0 for transport over cloud boundary (1)

Transport = Contact area x Flux

$$T(l_0) = S(l_0)\,F(l_0) \qquad \cong -S(l_0)\,K(l_0)\frac{\partial c}{\partial x}$$



8. Consequences for transport over cloud boundary (2)

$$T(l_0) = S(l_0)\,F(l_0) \quad \cong -S(l_0)\,K(l_0)\frac{\Delta c}{l_0}$$

$$S(l_0) = S_L\left(\frac{l_0}{L}\right)^{2-D_s} \qquad K(l_0) = l_0\,\delta u(l_0) \propto l_0\,\delta u(L)\left(\frac{l_0}{L}\right)^{1/3}$$

(Richardson Law)

$$\boxed{T(l_0) = \Delta c\,\delta u(L) S(L)\left(\frac{l_0}{L}\right)^{7/3-D_s} \qquad !!!!!}$$

No resolution dependancy for Ds=7/3!! Coincidence??

Conclusions

- LES models simulate the correct cloud geometry
- Cloud surface dimension D_s = 7/3
- Transport over cloud boundaries are scale independent within LES
- Repeating scaling arguments for l_0=h can be used as a heuristic proof for D_s = 7/3 (Use Reynolds number similarity (Sreenivasan et al, Proc Soc. London (1989)

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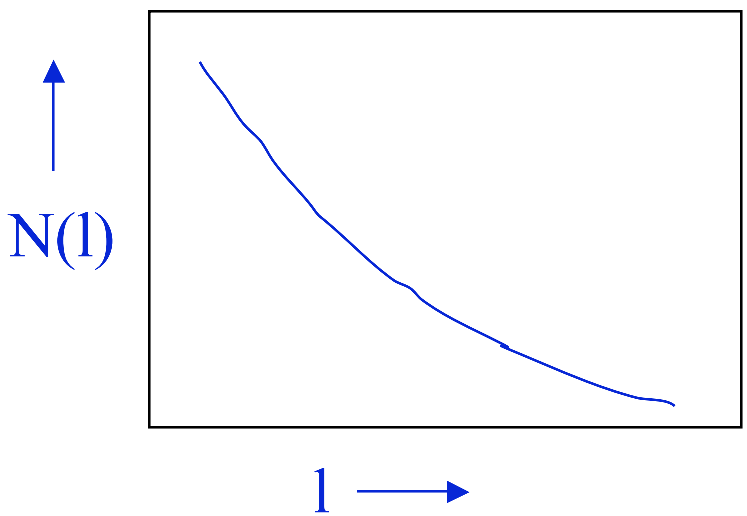
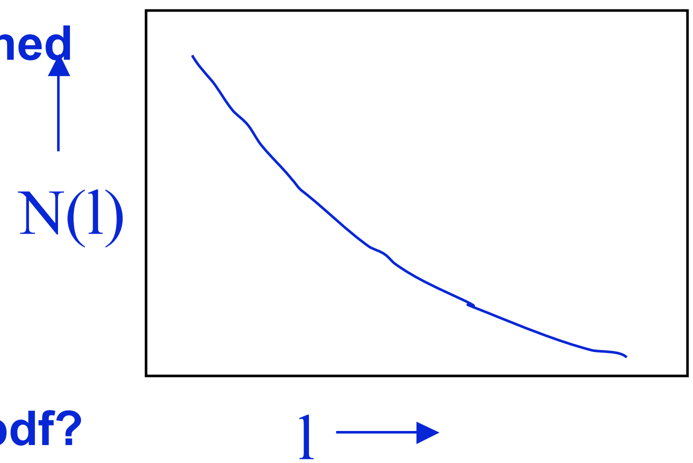
Cloud size distributions

- Many observational studies:
  - Exponential (Plank 1969, Wielicki and Welch 1986)
  - Log-normal (Lopez 1977)
  - Power law (Cahalan and Joseph 1989, Benner and Curry 1998)



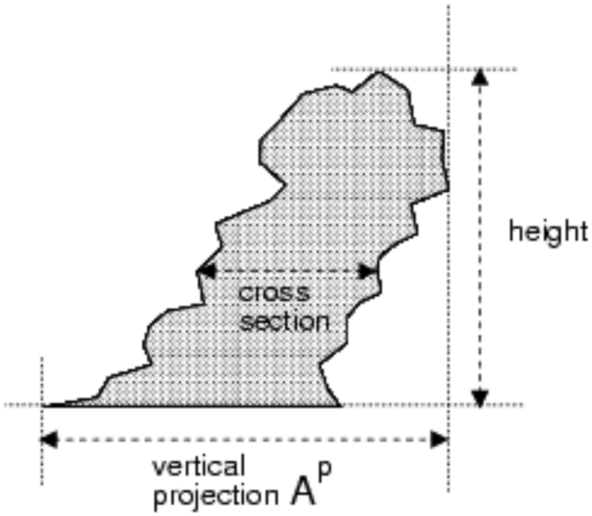
Cloud size distributions (2)

- Repeat with LES. Advantages
  - Controlled conditions
  - Statistics can be made arbitrary accurate
  - Link with dynamics can be established



- Specific Questions:
  - What is the functional form of the pdf?
  - What is the dominating size for the cloud cover?
  - Which clouds dominate the vertical transport?

Definitions:



Projection area of cloud n: A_n^p

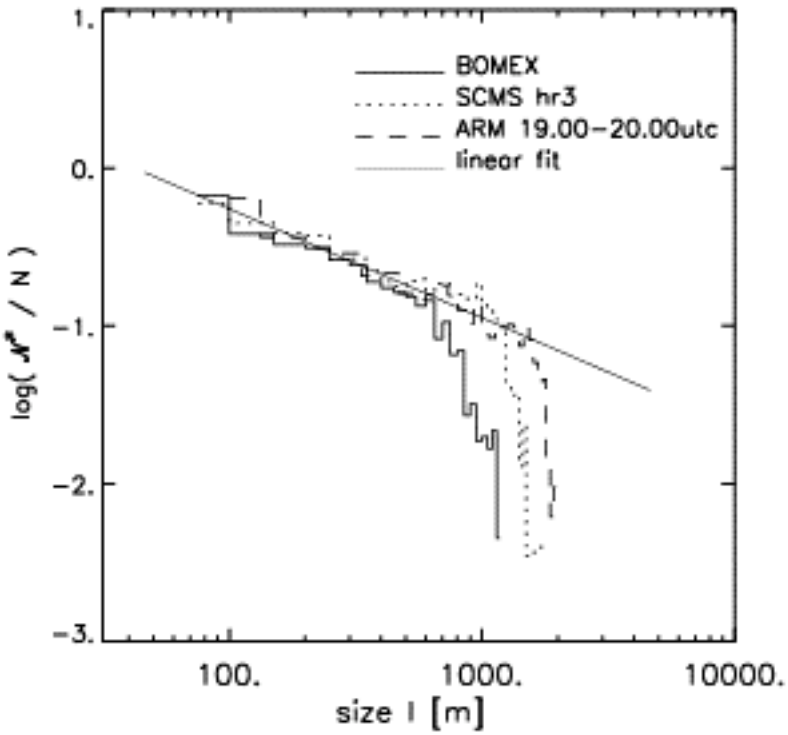
Size : $l_n \equiv \sqrt{A_n^p}$

Total number of clouds: $\mathbf{N} \equiv \int_0^\infty N(l)\,dl$

Cloud fraction: $\mathbf{a} \equiv \int_0^\infty \alpha(l)\,dl$

Related through: $\alpha(l) \equiv \dfrac{l^2 N(l)}{L_x L_y}$

Cloud Size Density



Typical Domain: 128x128x128

Number of clouds sampled: 35000

- Power law with b=-1.7

$$N(l) \propto l^b$$

- Scale break in all cases

- Scale break size l_d case dependant (700m~1250m)

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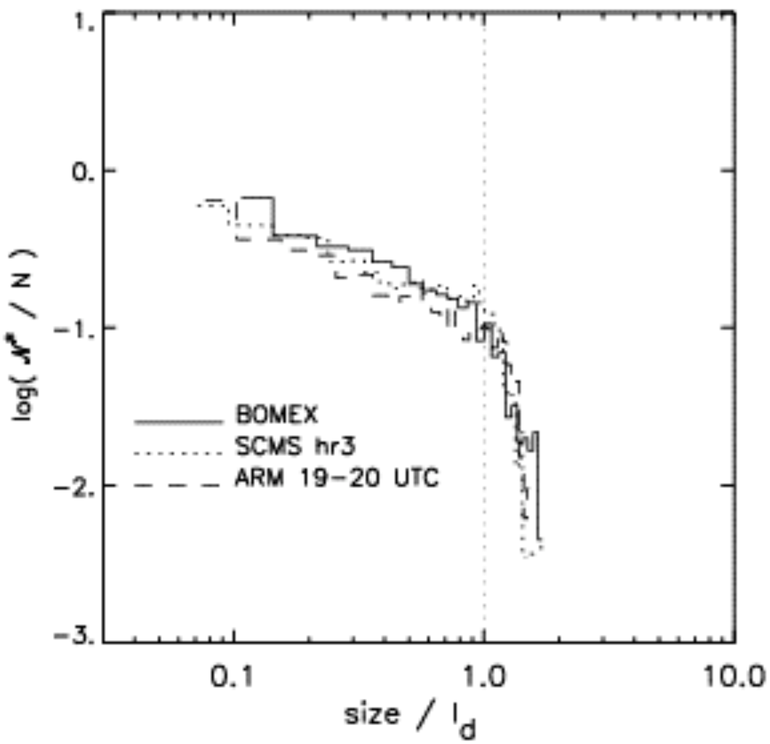
•••• Cloud size density (2)



•Universal pdf when rescaled with scale-break size l_d

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•••• Cloud Fraction density

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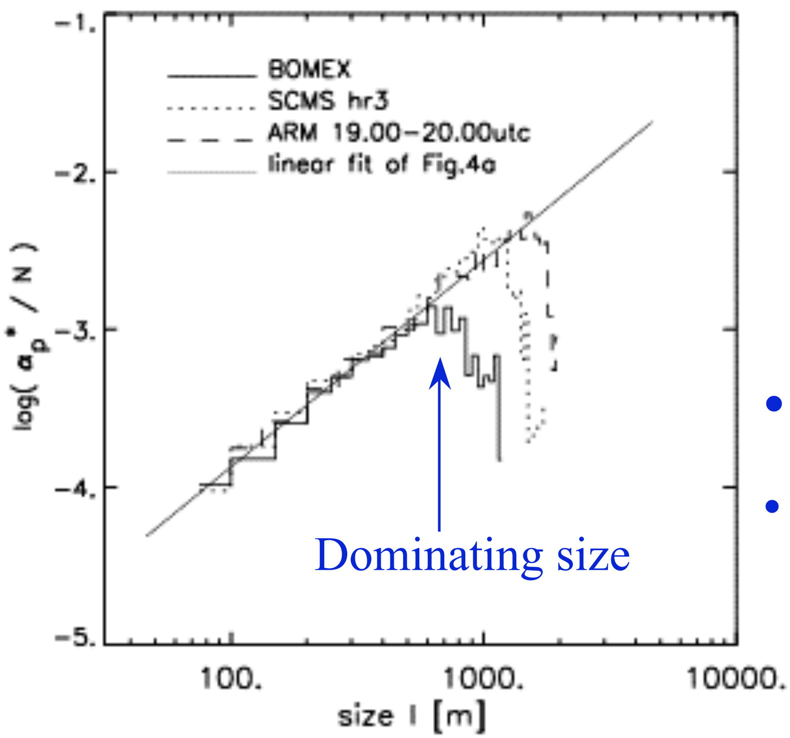

$$\alpha(l) = N(l)l^2 \propto l^{b+2}$$

With b=-1.7 (until scale break size)

- b<-2 smallest clouds dominate cloud cover
- b>-2 largest clouds dominate cloud cover

Due to scale break there is a intermediate dominating size

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Conclusions

•Cloud size distribution: $N(l) \propto l^b$ with b=-1.7

•Non-universal scale break size beyond which the number density falls off stronger. (Only free parameter left)

•No resolution dependency has been found (see paper)

•Intermediated cloud size has been found which dominates the cloud fraction.

Open Questions:

•What is the physics behind the power law of the cloud density distribution?

•What is causing the scale break?

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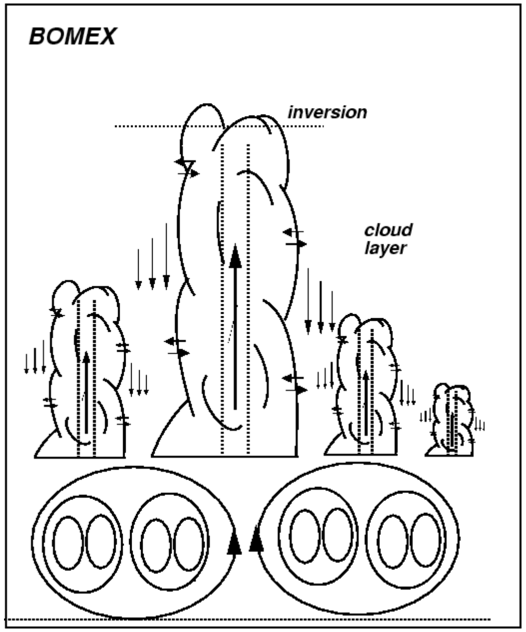
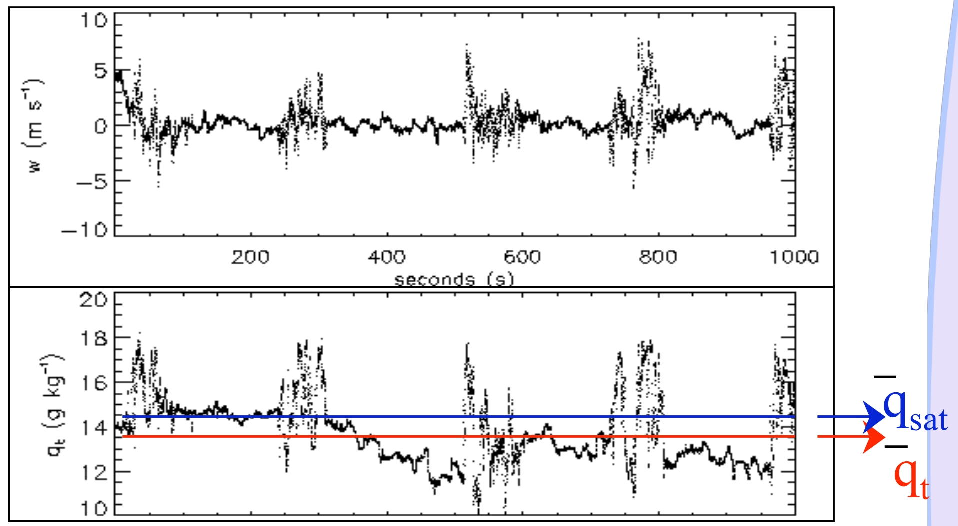
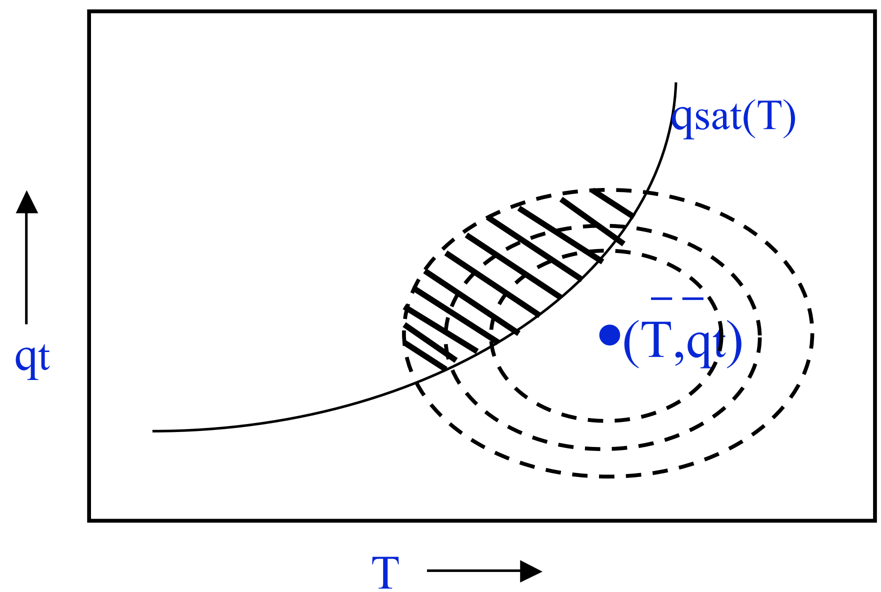
•••• How to use this cloud variability to build cloud and radiation parameterizations? :





Statistical cloud schemes



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Statistical Cloud Schemes (2):

Convenient to introduce:

"The distance to the saturation curve"

$$s \equiv q_t - q_s(p,T)$$

Normalise s by its variance:

$$\boxed{Q \equiv \bar{t} \equiv \frac{\overline{q}_t - \overline{q}_s}{\sigma_s} \quad \text{Sommeria and Deardorf (JAS,1976)}}$$

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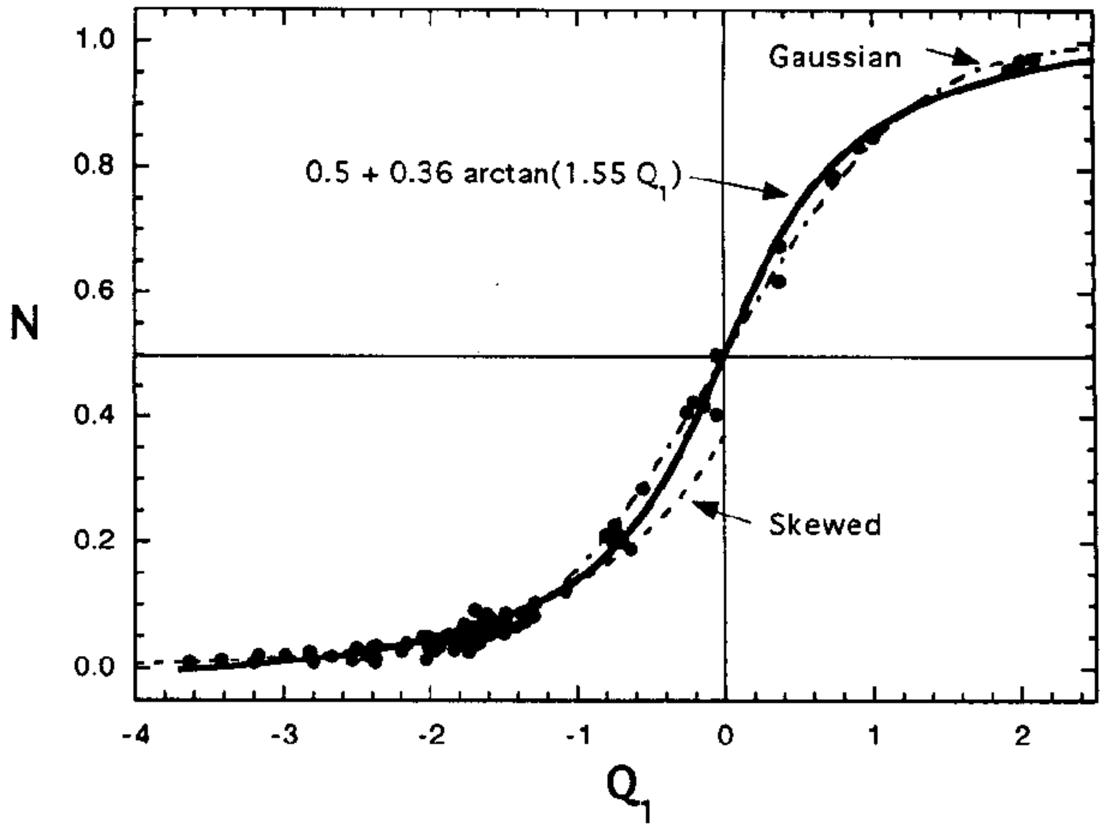
Verification (with LES)



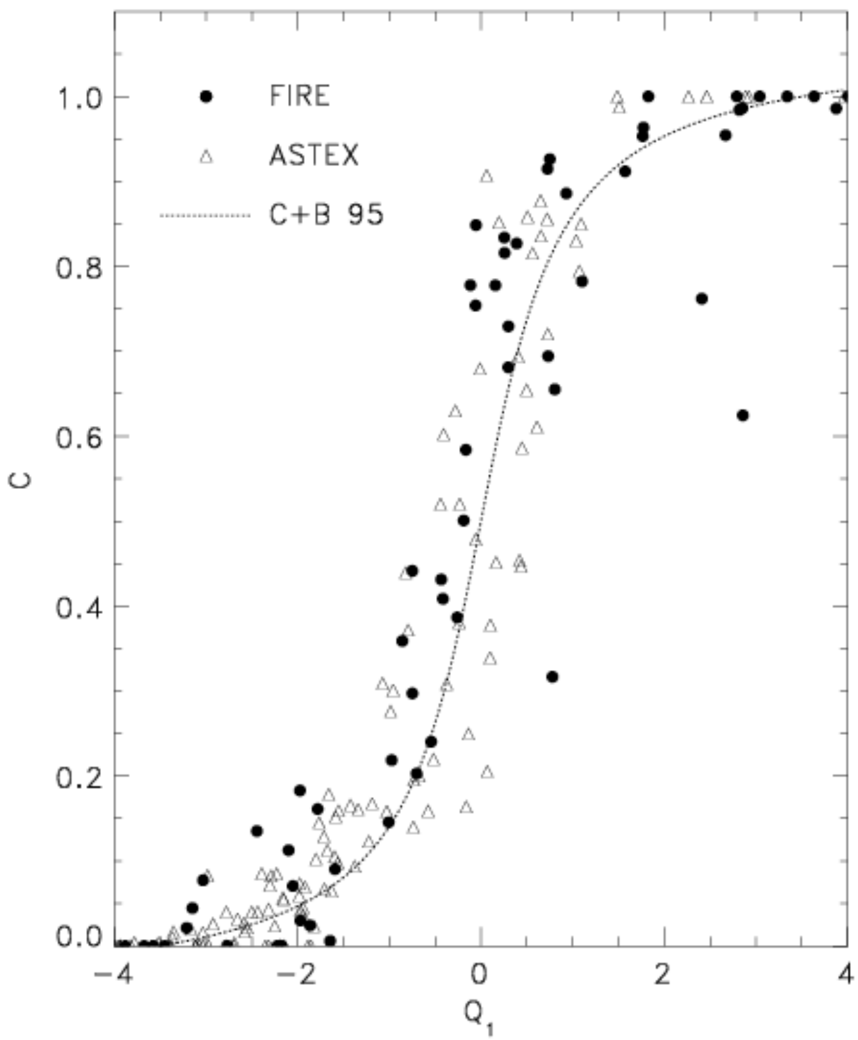
Cloud cover

$$Q \equiv \bar{t} \equiv \frac{\overline{q}_t - \overline{q}_s}{\sigma_s}$$

Bechtold and Cuijpers JAS 1995

Bechtold and Siebesma JAS 1999

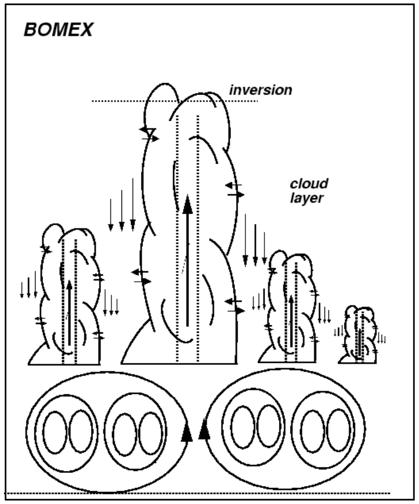
Verification (with Observations)



Wood, Field and Cotton 2002 Atm. Research

Remarks:

1. Gaussian PDF “good enough” to estimate liquid water and cloud cover.
2. Correct limit: if $dx \Rightarrow 0 \; then \; \sigma_s \Rightarrow 0$ and the scheme converges to the all-or-nothing limit
3. Parameterization problem reduced to finding the subgrid variability, i.e. finding σ_s .



$$a_c = f\left(\frac{\overline{q}_t - \overline{q}_s}{\sigma_s}\right)$$

$$q_l = g\left(\frac{\overline{q}_t - \overline{q}_s}{\sigma_s}\right)$$

$$R(\overline{q}_t, \sigma_s)$$

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Convection and turbulence parameterization give estimate of σ_s → **Cloud scheme :** → **radiation scheme :**

McICA by employing the variance

- **Subgrid variability (at least the 2nd moment) for the thermodynamic variables needs to be taken into acount in any GCM for parameterizations of convection, clouds and radiation in a consistent way.**

- **At present this has not be accomplished in any GCM.**

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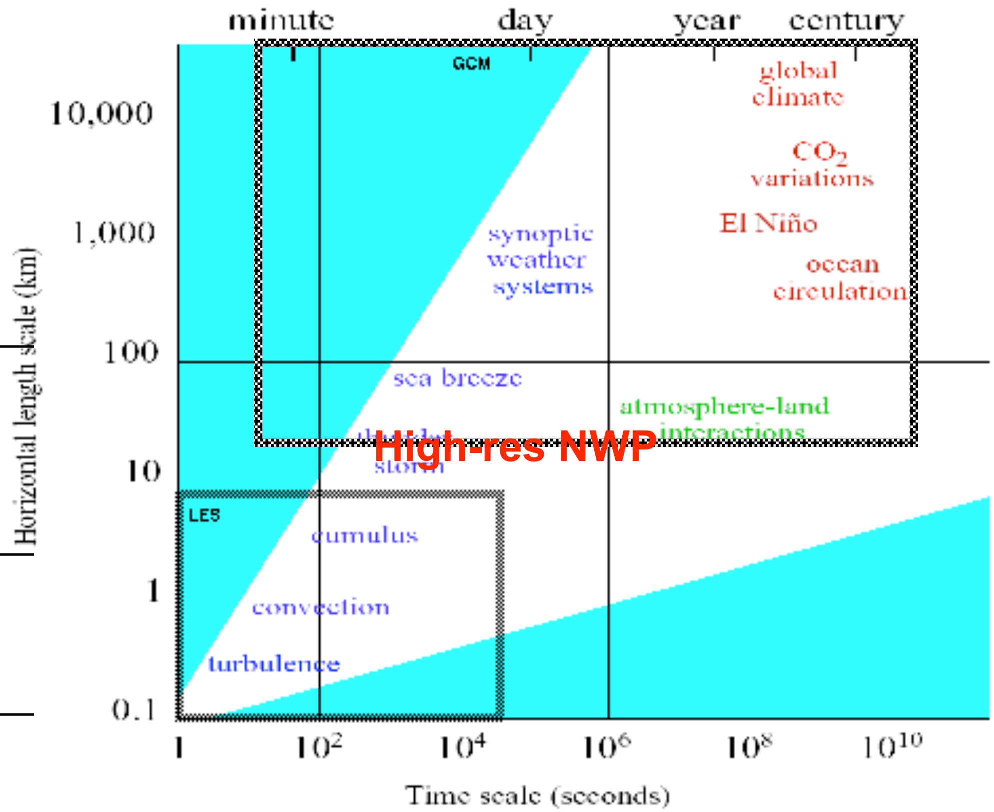
How does the variability change with resolution?



$\sigma_s \approx ?$

$\sigma_s \approx ?$

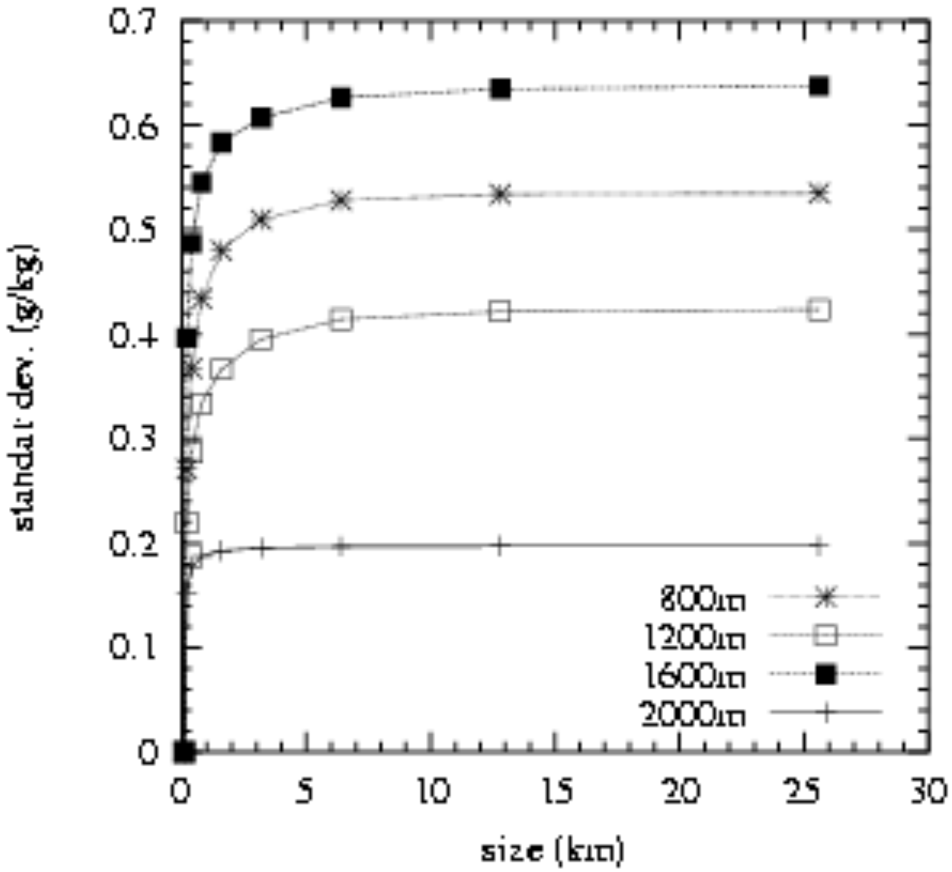
$\sigma_s \approx 0$

All or nothing

Calculate in LES : $\langle \sigma_q(l) \rangle$

....

$$\langle \sigma_q(l) \rangle$$



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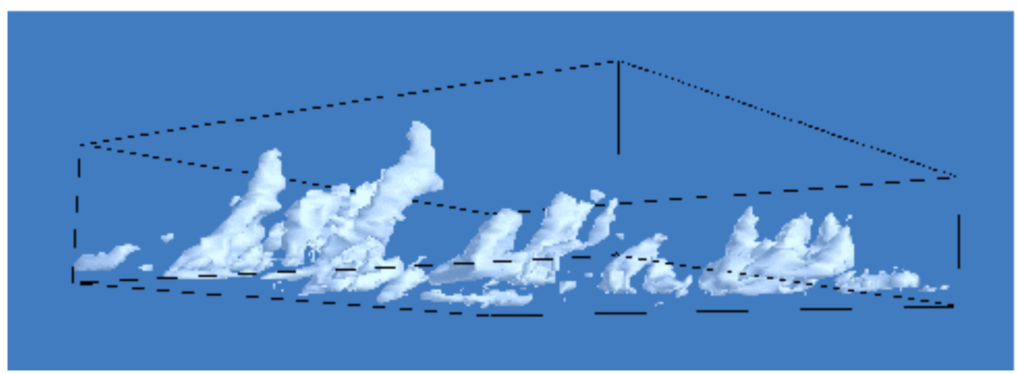
No growth of $\langle \sigma_q(l) \rangle$

For size l > 5 km



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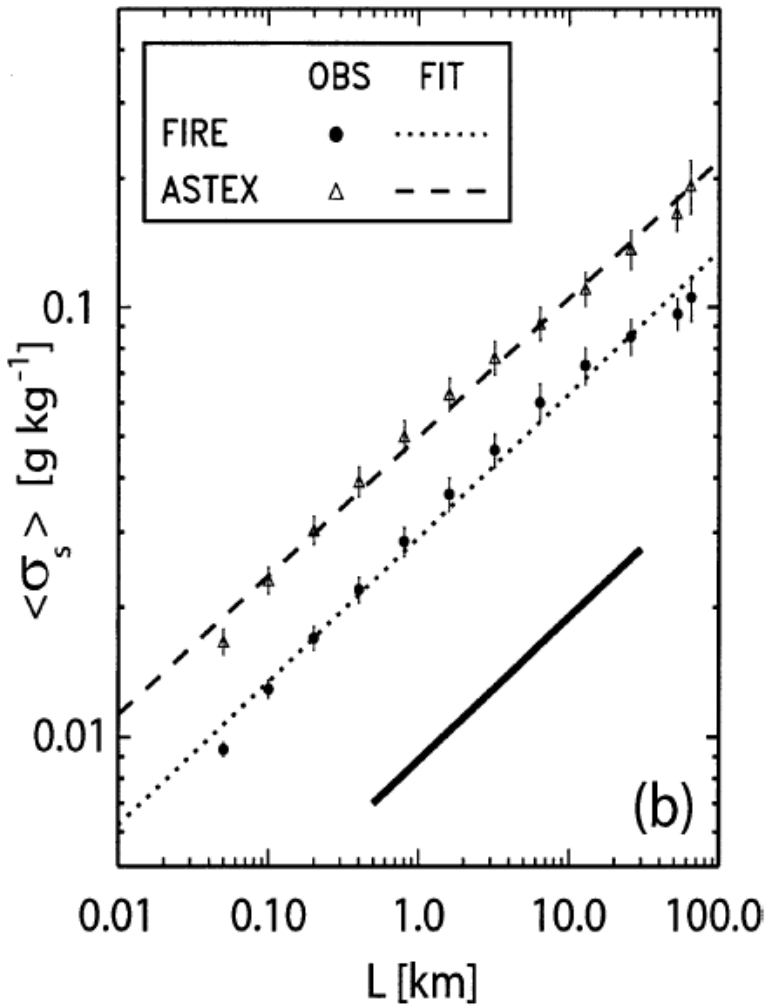
How about Stratocumulus?



Observations give :

Standard deviation of

s (=qt-qs) scales as

$s \sim L^{1/3}$

from 100m up to 100km, consistent with a 5/3 spectrum over this range.

Mesoscale Organisation!!

How about LES??

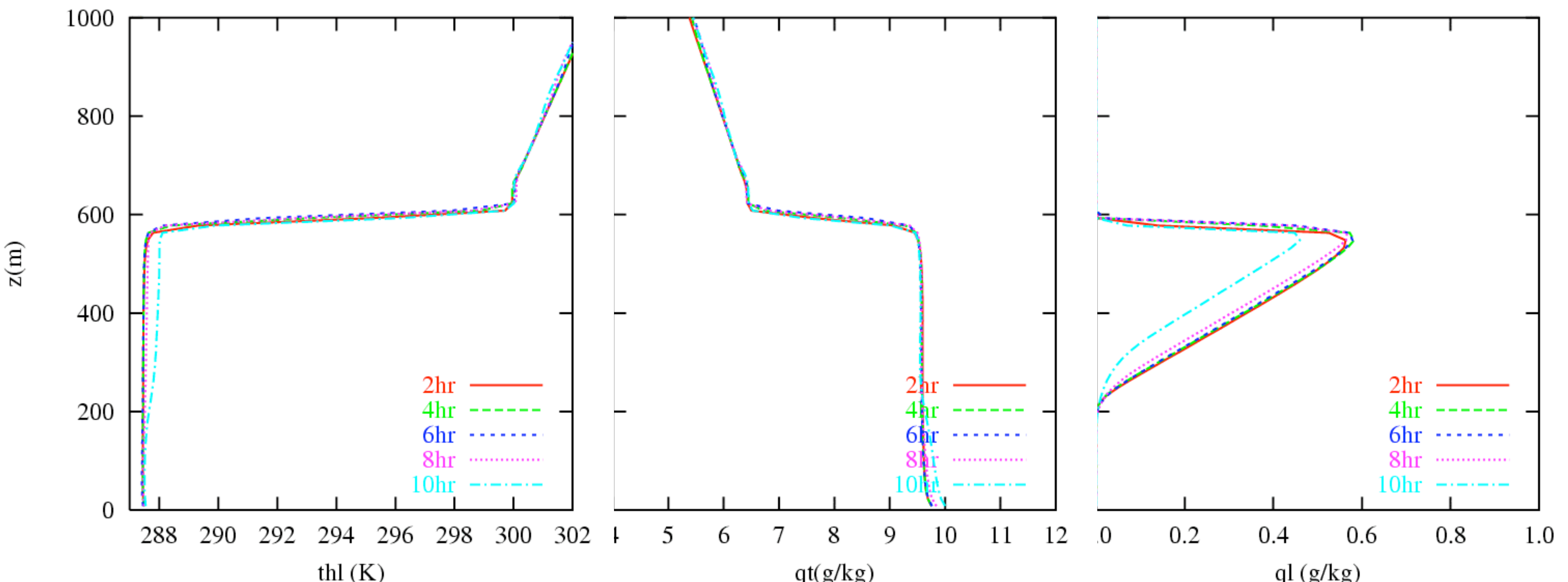
- Wood, Field and Cotton 2002 Atm. Research

Davies, Marshak and Cahalan JAS 53 1996

Large-Eddy Simulations

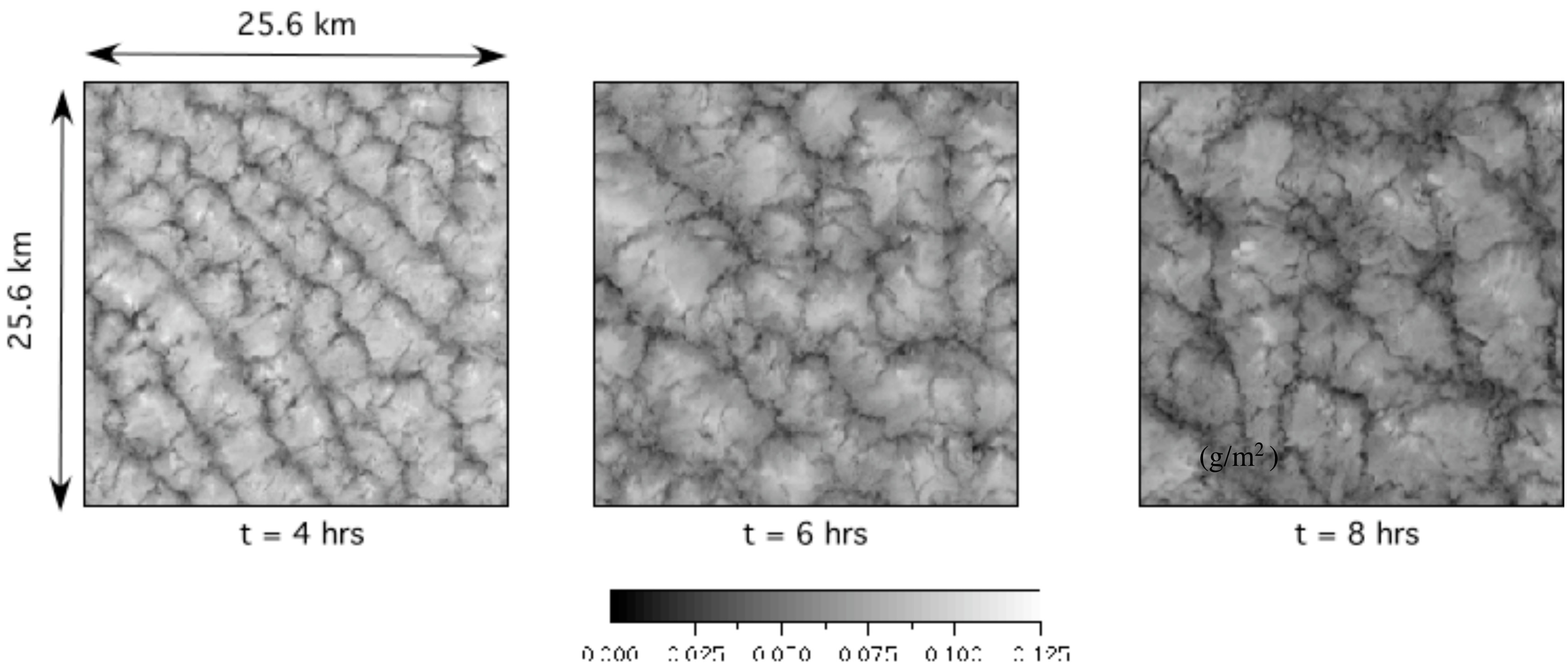
- Parallelized version
- Large horizontal domain 25.6 x 25.6 km^2
- Number of grid points 256 x 256 x 80
- $\Delta x = \Delta y = 100m$, $\Delta z < 20$ m
- Cylic boundary conditions
- Simulation time 10 hours

Nocturnal stratocumulus cloud layer, initialization based on observations (FIRE I)



LES does show mesoscale growth

Liquid water path evolution in stratocumulus simulation



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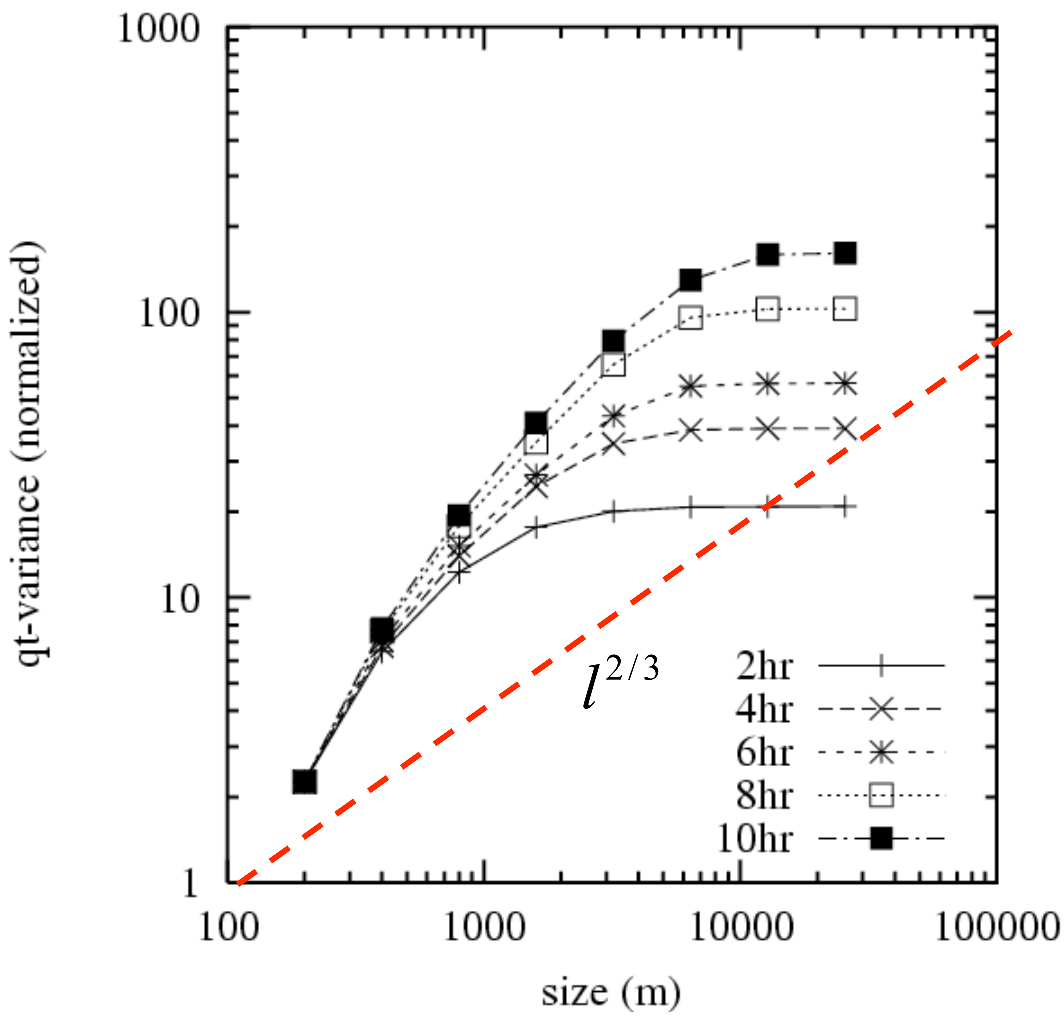
Same analysis as Wood et. al



$$\frac{\sigma_s^2(l)}{\sigma_s^2(l_0)} \quad vs \quad l \quad (\propto l^{2/3}?)$$

- Variance grows with scale and time

- But …. Not with the expected scaling!!

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Conclusions

•LES does produce realistic cloud structures

•GCSS provides a large data set of 3d cloud scenes that can be used for radiative transfer studies

•GCM's are still in a poor state concerning cloud inhomogeneity effects

•Simultaneous measurements of cloud structures and radiation measurements offers a strong constraint for cloud-radiation effects that will reduce the infamous "tuning-freedom"

•ATEX :

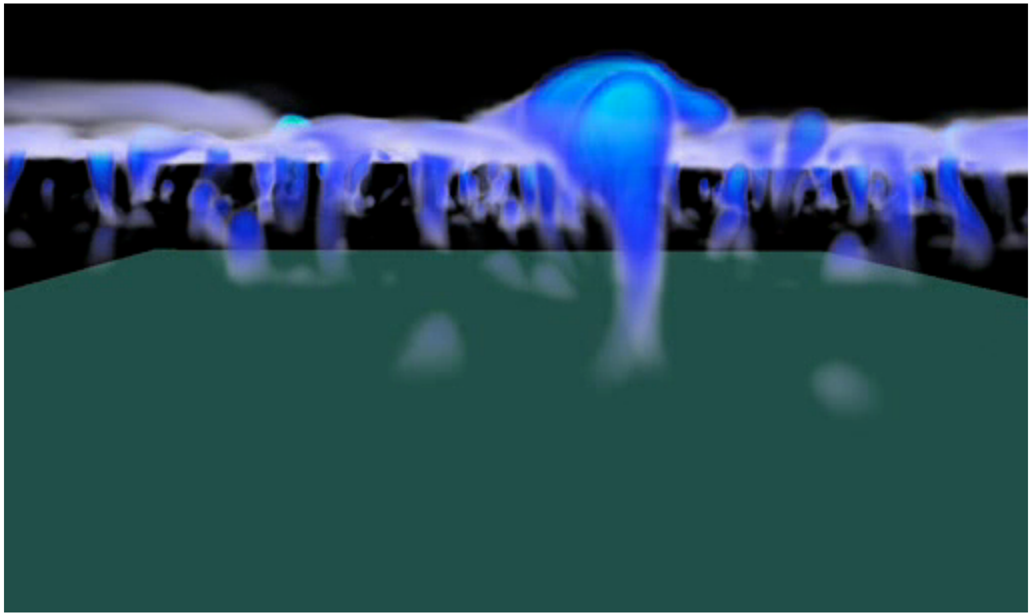
Marine

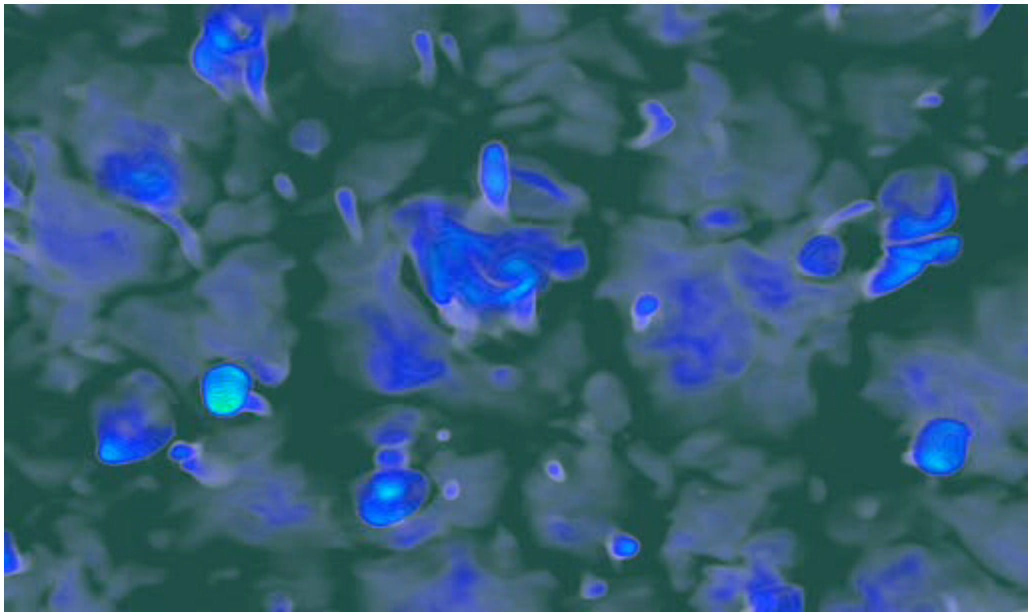
Cumulus

Topped

With

Scu





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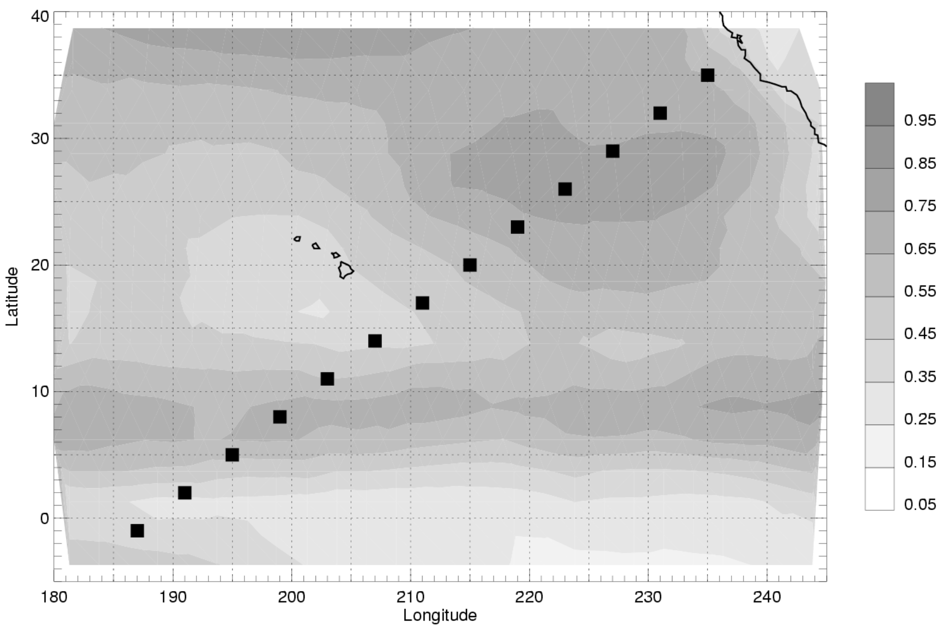
Courtesy : Dave Stevens ; Lawrence Livermore National Laboratory

EUROCS Model Evaluation:

Hadley Circulation in the Pacific:

- Well defined large scale circulation
- Monthly mean deviations from climatology relatively small
- All studied cloud types within EUROCS are present in well geographically seperated way.
- Future Changes in Climate for Europe are connected with changes in the Hadley Circulation (see Dutch Challenge Project)

Use JJA 1998 as an example:

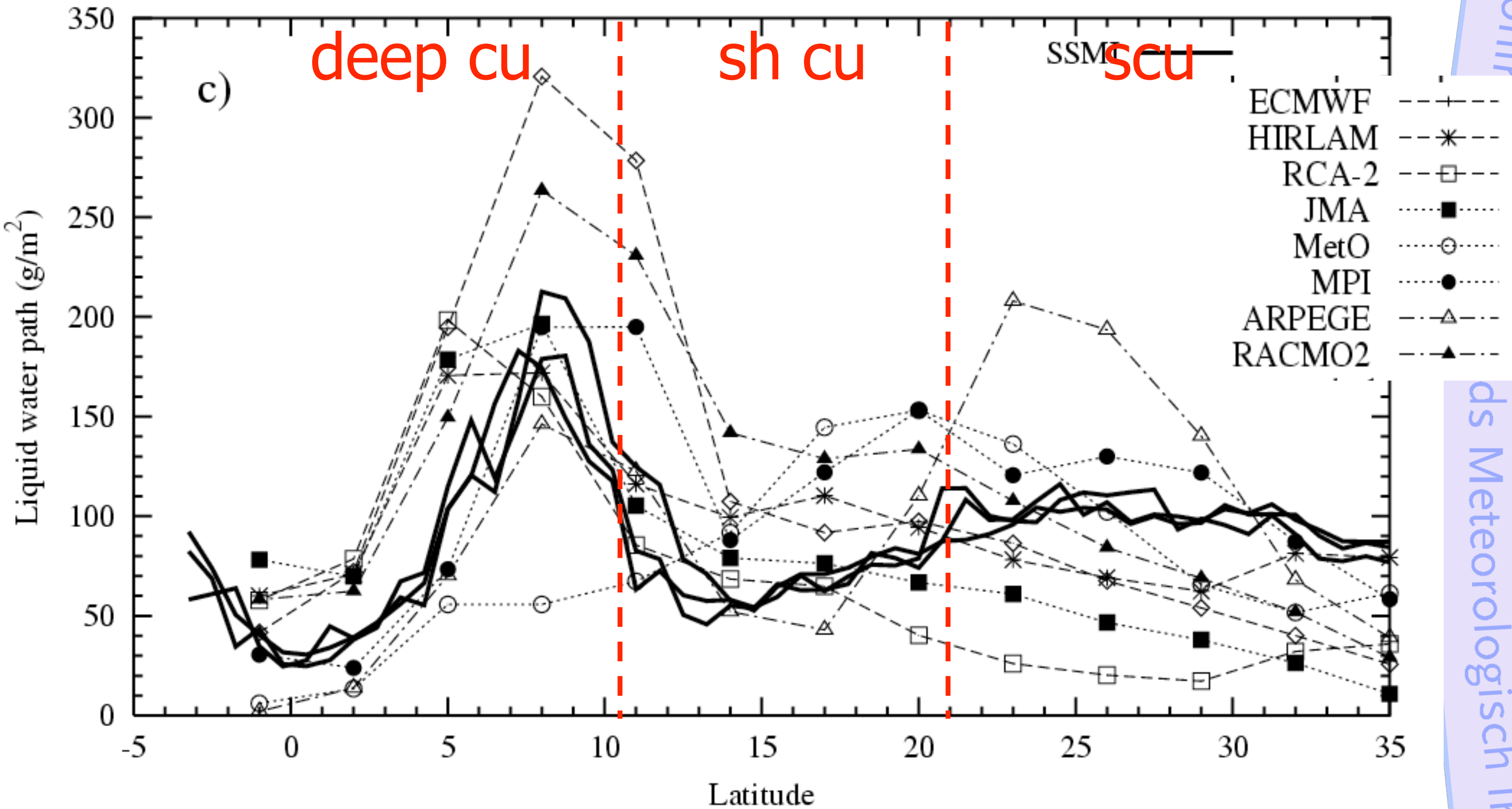


Monthly means for JJA 1998
for 13 gridpoint columns.
required output: *vertical profiles*
single level parameters

(Siebesma and coauthors:QJRMS november 2004.)

www.knmi.nl/samenw/eurocs

Liquid water Path



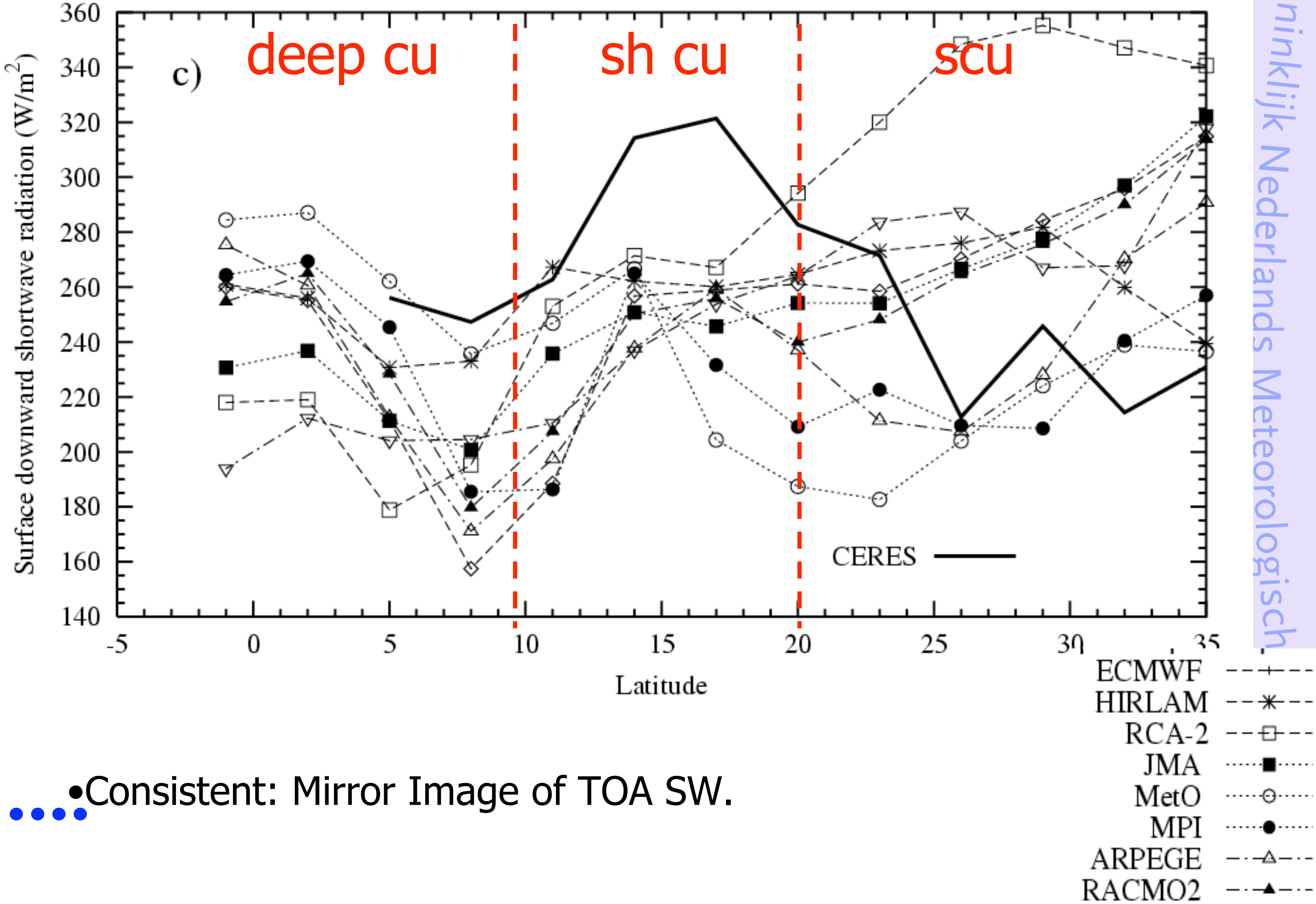
ECMWF, RACMO: too high

MetO : too low

Too high

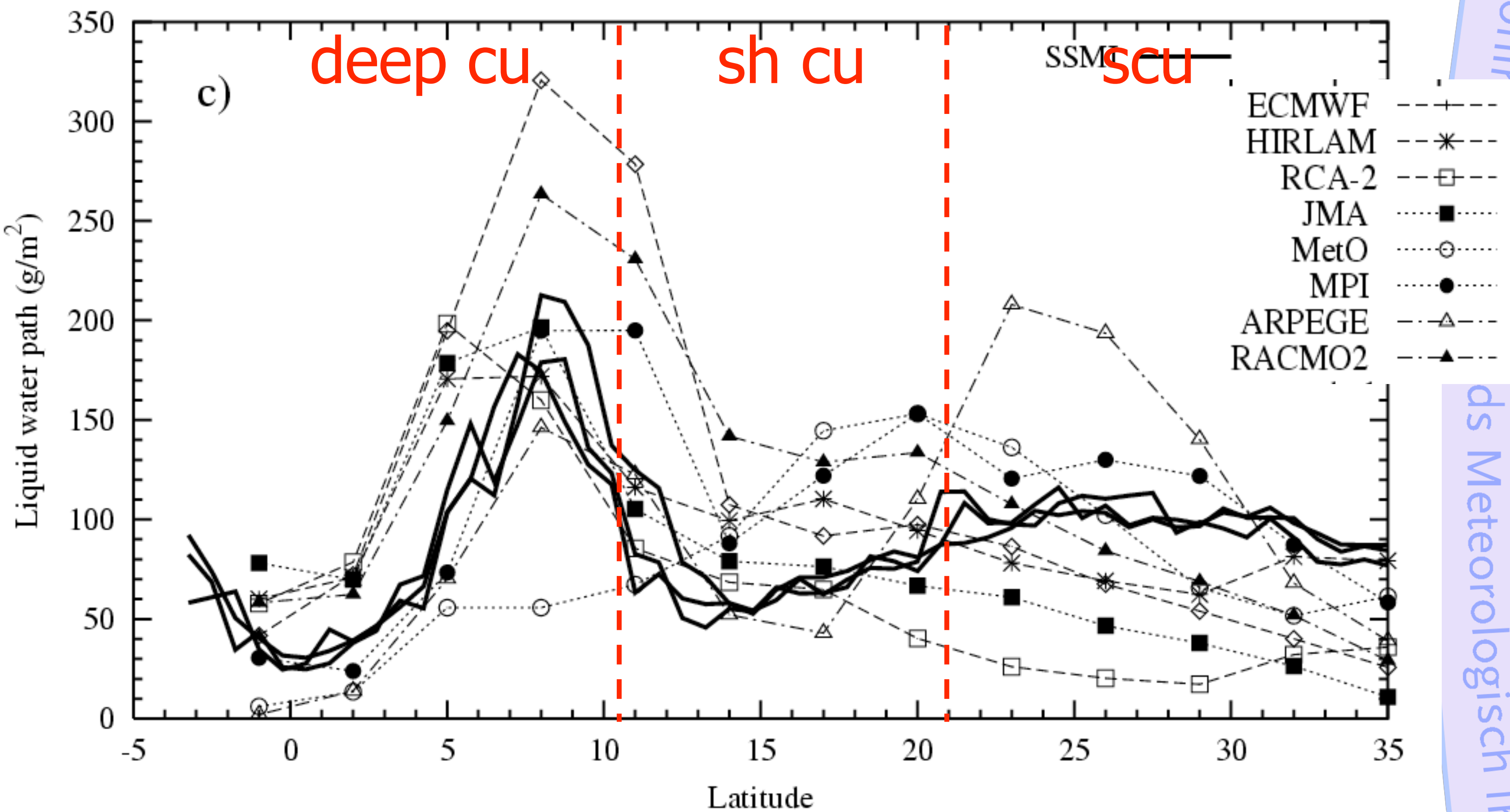
Too low

Surface downward shortwave Radiation



- Consistent: Mirror Image of TOA SW.

Liquid water Path



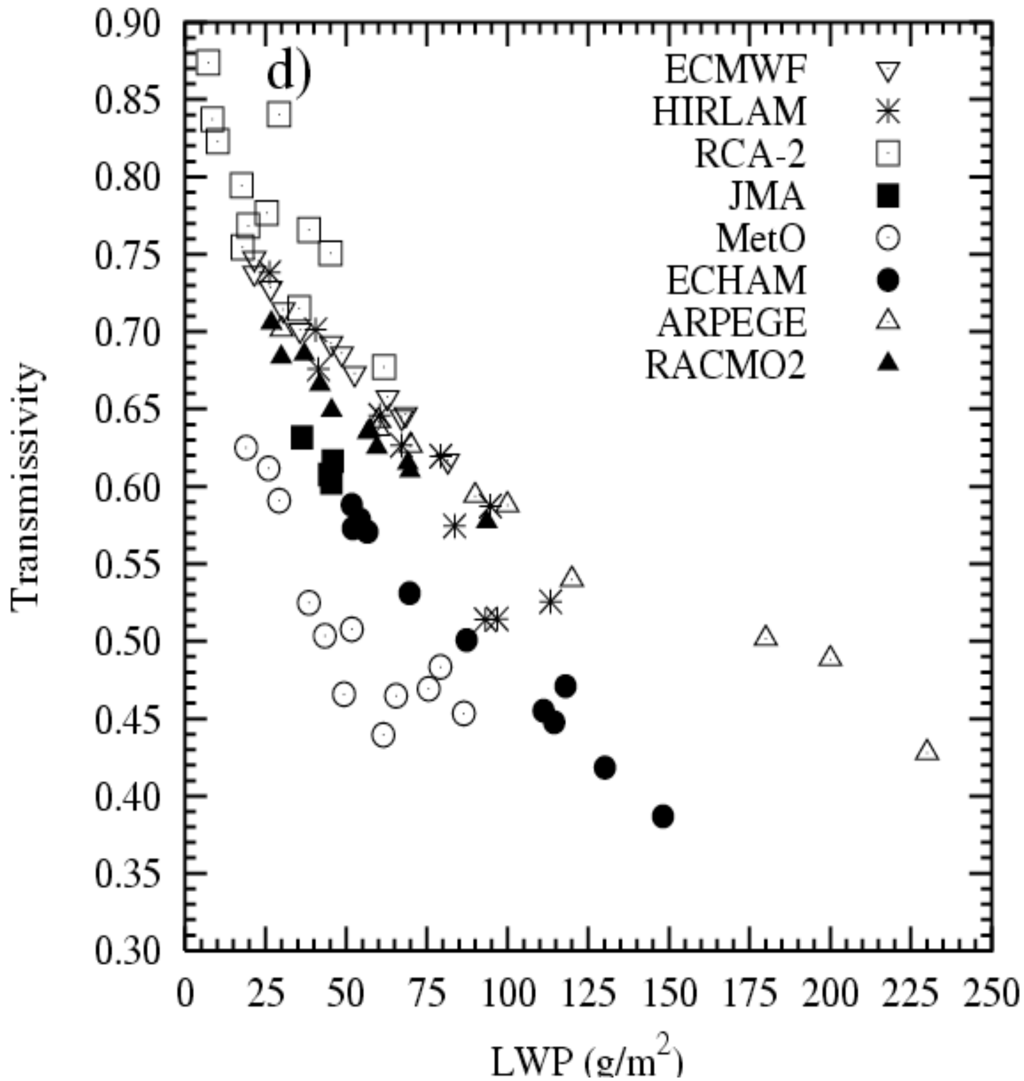
ECMWF, RACMO: too high

MetO : too low

Too high

Too low

Scatter plot: LWP versus Transmissivity.

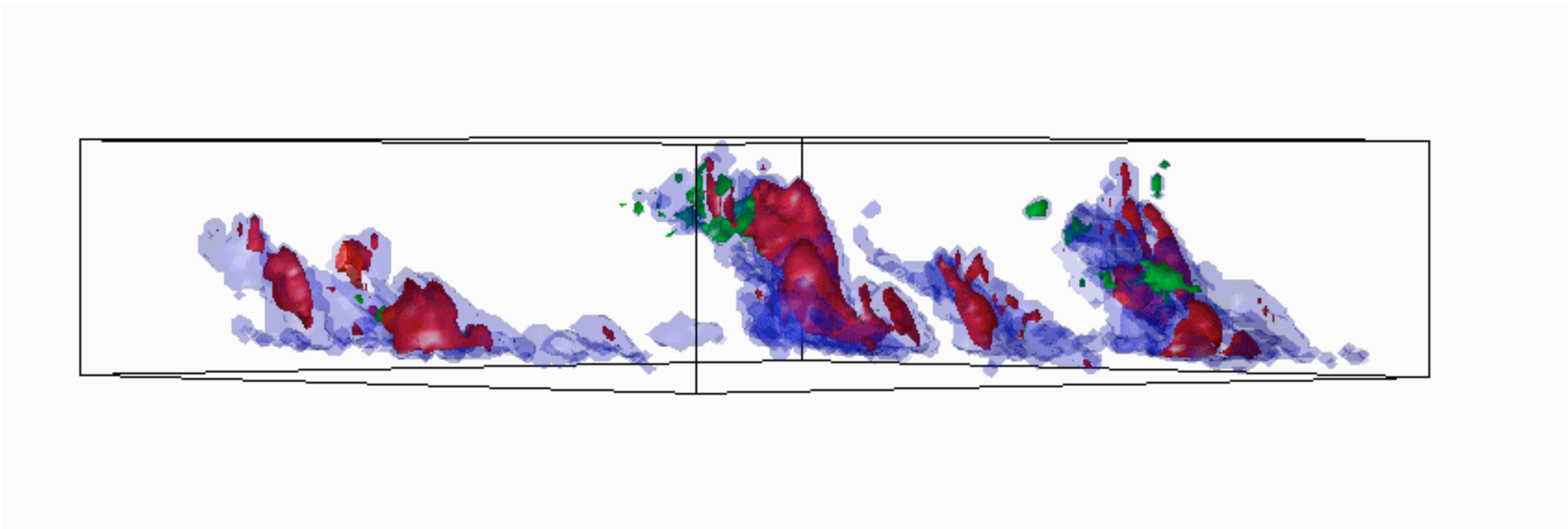


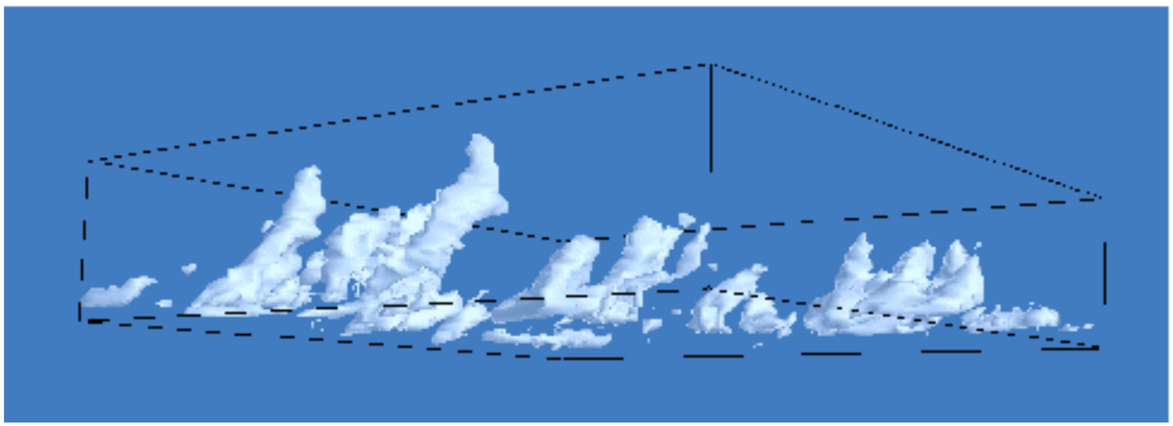
$$T = \frac{\left\langle F_{rad,sw,down,srf} \right\rangle}{\left\langle F_{rad,sw,down,toa} \right\rangle}$$

With:

<..> = monthly time averages over [9hr,15hr] local time

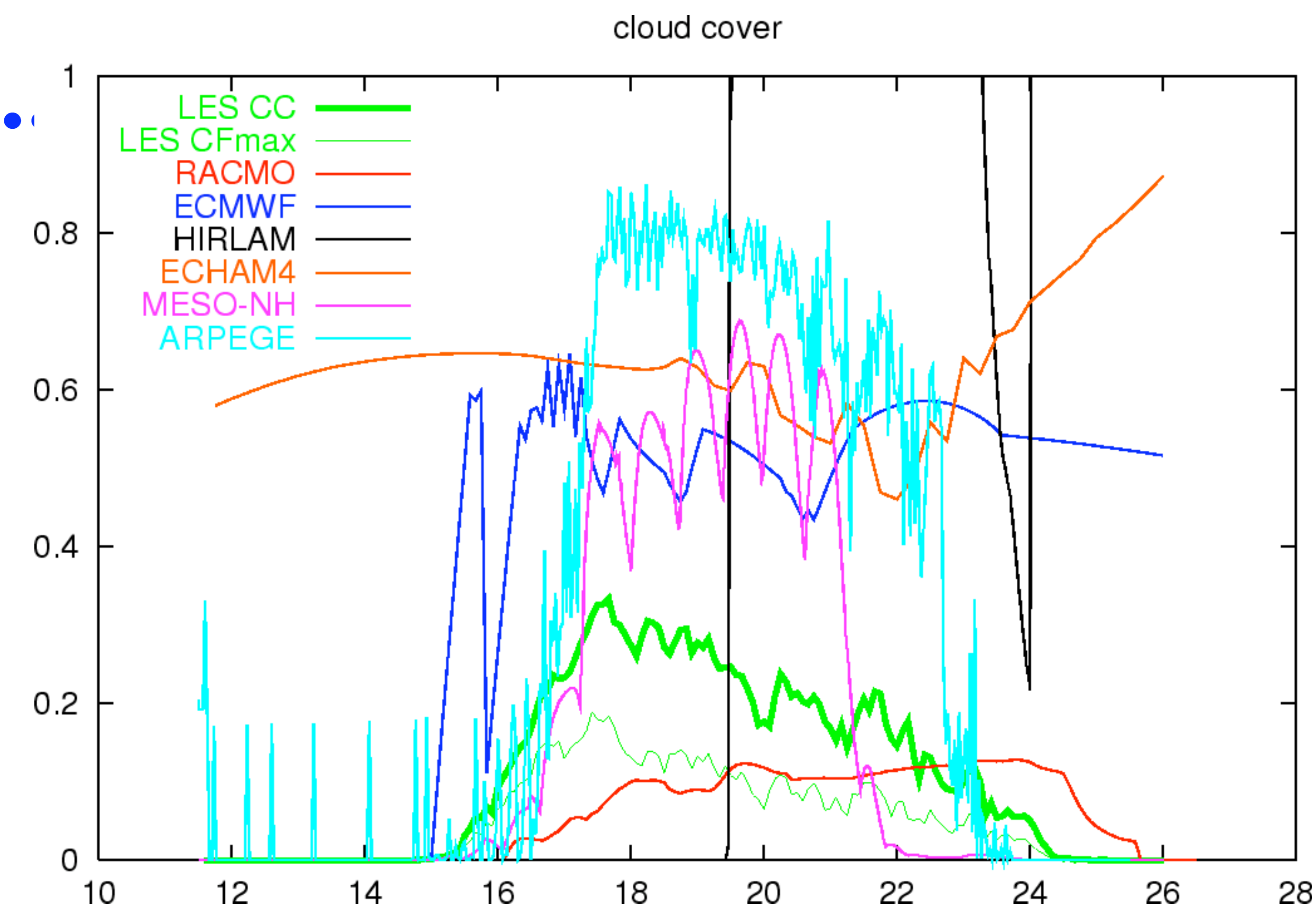
- Clouds in MetO and ECHAM are too reflective
- Differences in radiation schemes! Tuning?!





LES run of diurnal cycle of cumulus:

ARM site Oklahoma June 21 1997



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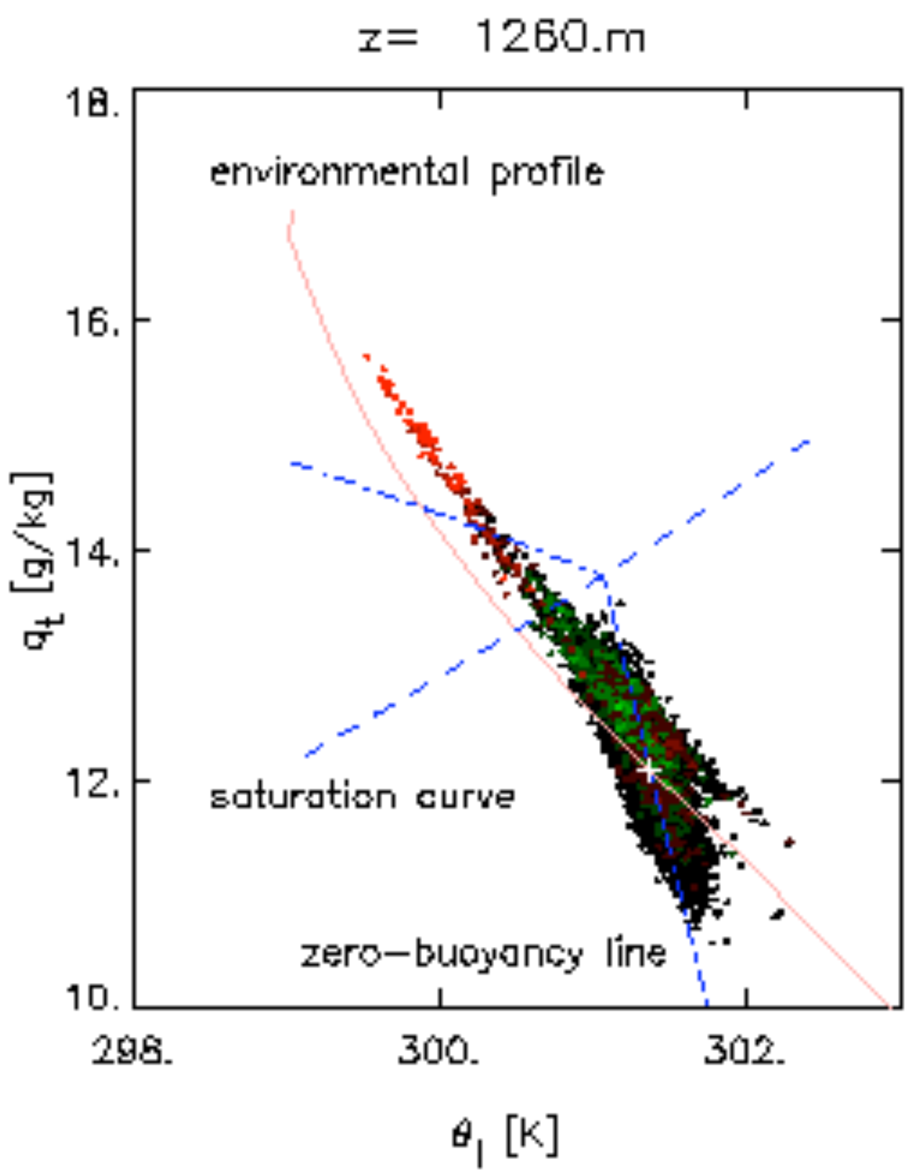
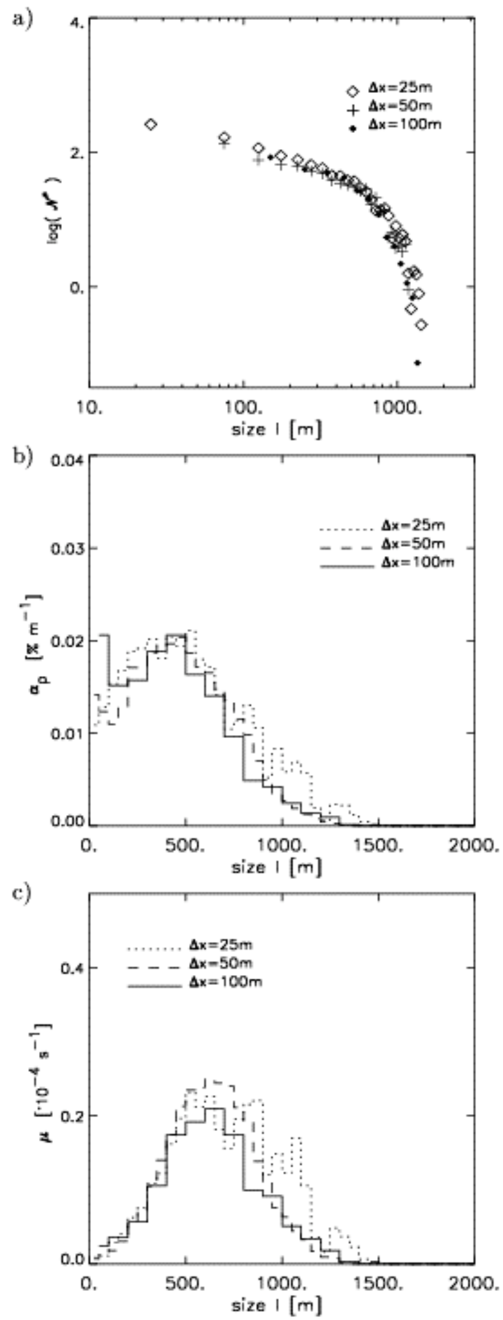
Intercomparison results for 1D-model versions of GCM's

(for details see http:/www.knmi.nl/samenw/eurocs)



z= 1260.m
environmental profile
saturation curve
zero−buoyancy line
18.
16.
14.
12.
10.
298.
300.
302.
q_t [g/kg]
θ_l [K]

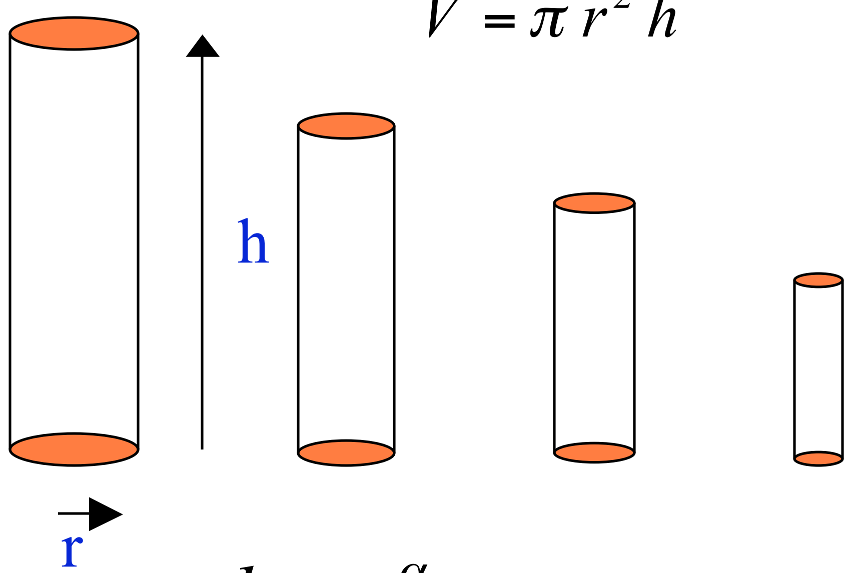

a)
b)
c)
Δx=25m
Δx=50m
Δx=100m
size l [m]
10.
100.
1000.
0.
500.
1000.
1500.
2000.

F

Not a complete demonstration of the fact that clouds are fractal! Nature could play the following trick om us:

$$A = 2\pi\, r\, h$$

$$V = \pi\, r^2\, h$$



$$h \propto r^{\alpha}$$

Remember: $l \cong V^{1/3}$

$$A \propto l^{\frac{3(1+\alpha)}{2+\alpha}}$$

$$with \quad \alpha = 5/2$$

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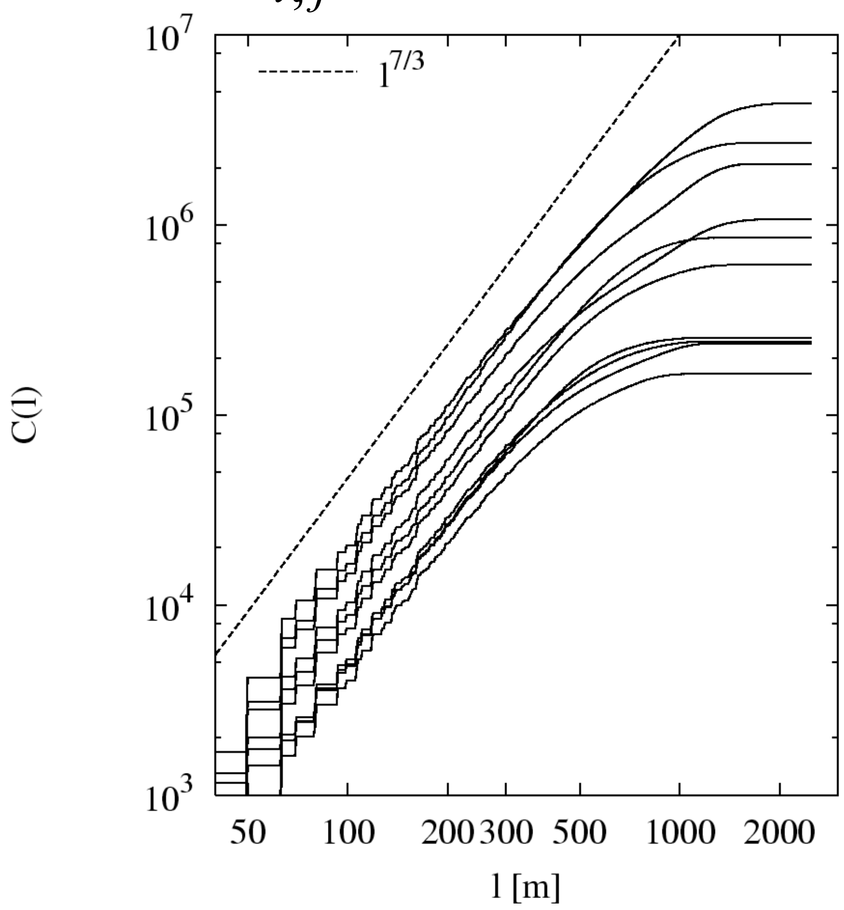
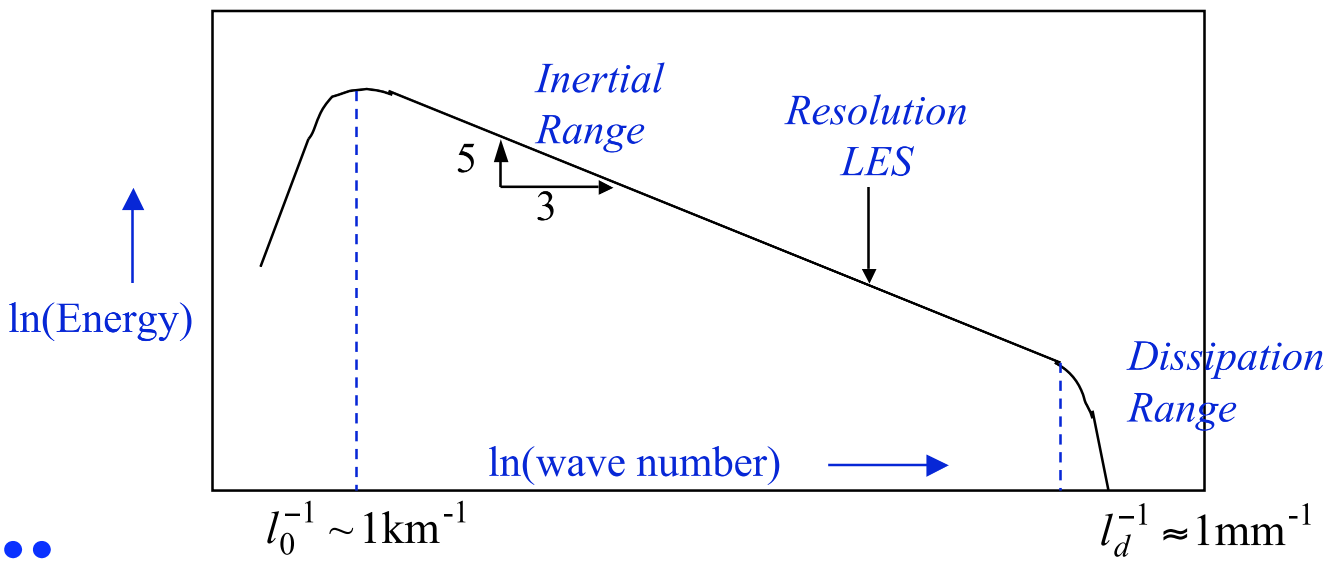
6. Direct measurement of correlation dimension

$$C(l) = \sum_{i,j} \theta\left(l - \left|\vec{x}_i - \vec{x}_j\right|\right) \propto \ell^{D_s}$$



Large Eddy Simulation (LES) Modelling

- High Resolution Non-hydrostatic Model: ~50m
- Large eddies explicitly resolved by NS-equations
- inertial range partially resolved
- Therefore: subgrid eddies can be realistically parametrised by using Kolmogorov theory



CLOUDS in GCM's: What are the problems?

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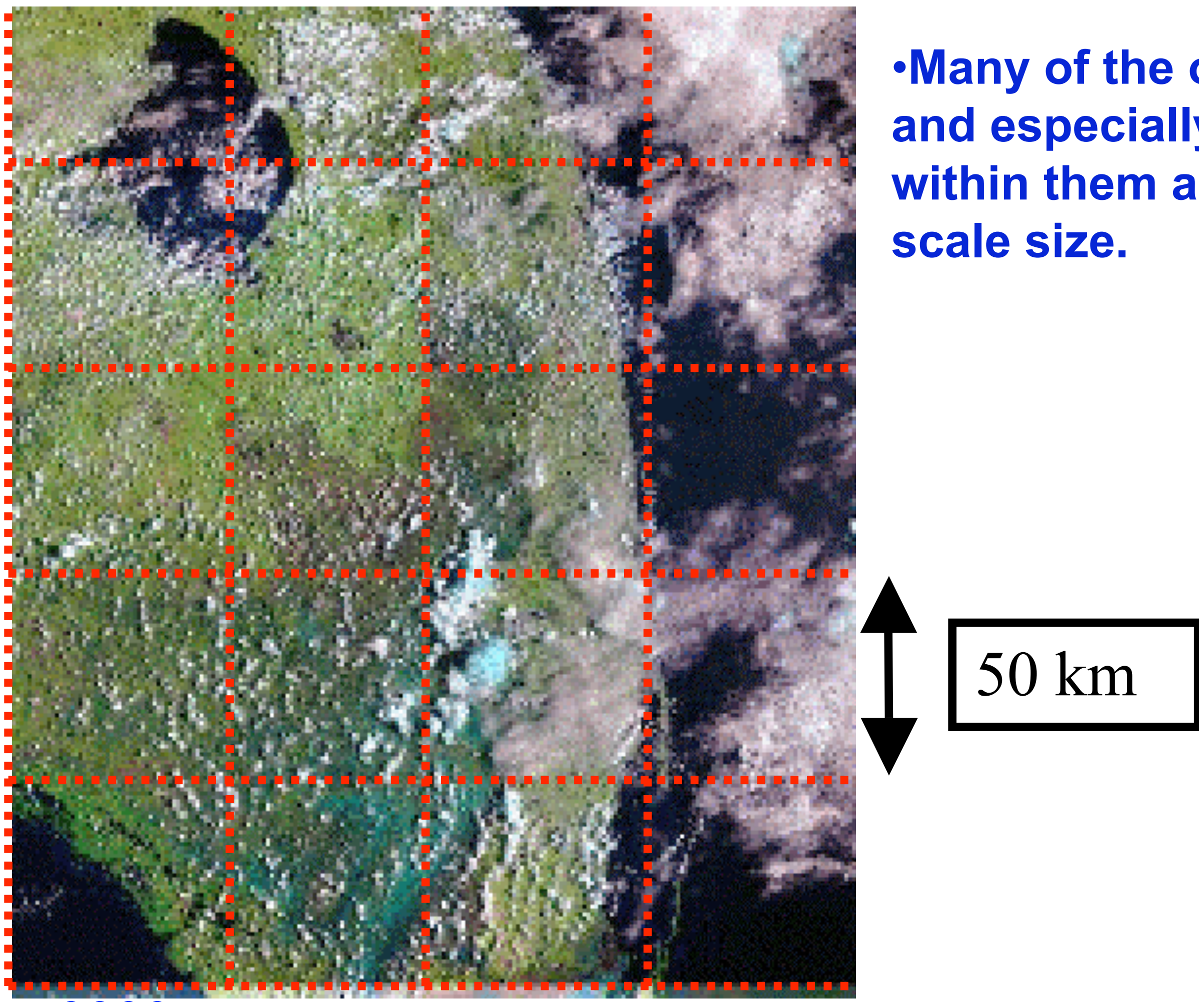


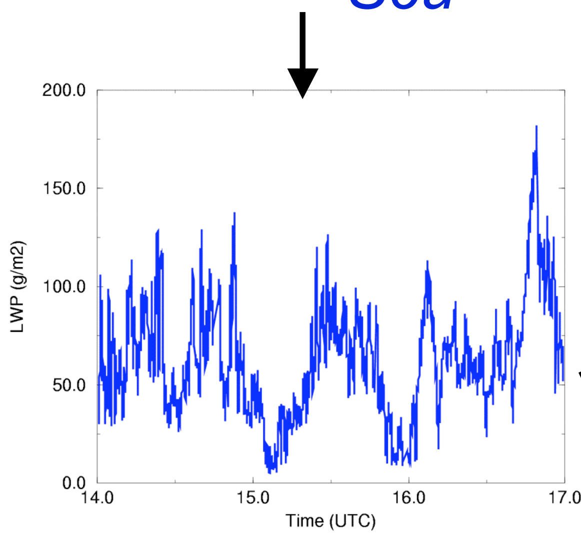
•Many of the observed clouds and especially the processes within them are of sub grid-scale size.

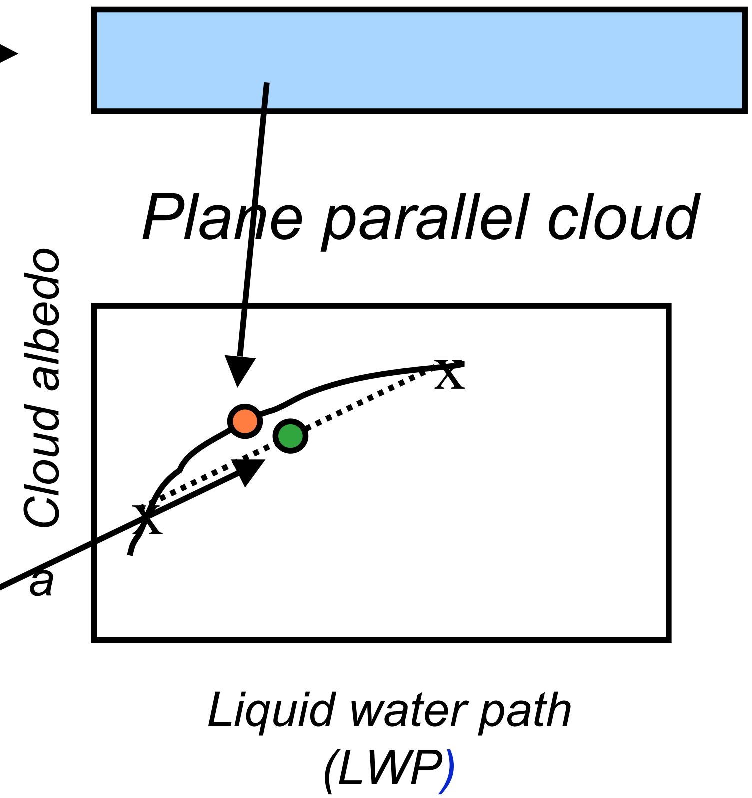
Neglecting this subgrid variability causes biased errors in a number of key processes:

- Moist convection of heat and moisture
- Cloud Properties
- Radiative Transport

Cloud albedo bias

Scu





$$\overline{a(LWP)} < a(\overline{LWP})$$

Neglecting Cloud inhomogeneity causes a positive bias in the cloud albedo.

••••

•Subgrid variability (at least the 2nd moment) for the thermodynamic variables needs to be taken into acount in any GCM for parameterizations of convection, clouds and radiation in a consistent way.

•At present this has not be accomplished in any GCM.

•Large Eddy Simulations (LES) in combination with observations is a useful tool to obtain this subgrid variability and to help develop GCM parameterizations for these cloud related processes.

•GEWEX Cloud System Studies (GCSS) explores this avenue (www.gewex.org/gcss.html)

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How to obtain a parameterization for the variance?

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Link it to the convection/turbulence schemes using a variance budget:

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Production Dissipation

$$\overline{w'q_t'}\frac{\partial q_t}{\partial z} = \tau^{-1}\overline{q_t'^2}$$

$$\tau = l_{cloud} / w_*^{cu}$$

$$w_*^{cu} = \int_{cloud} \frac{g}{\theta} M \Delta\theta_v dz$$

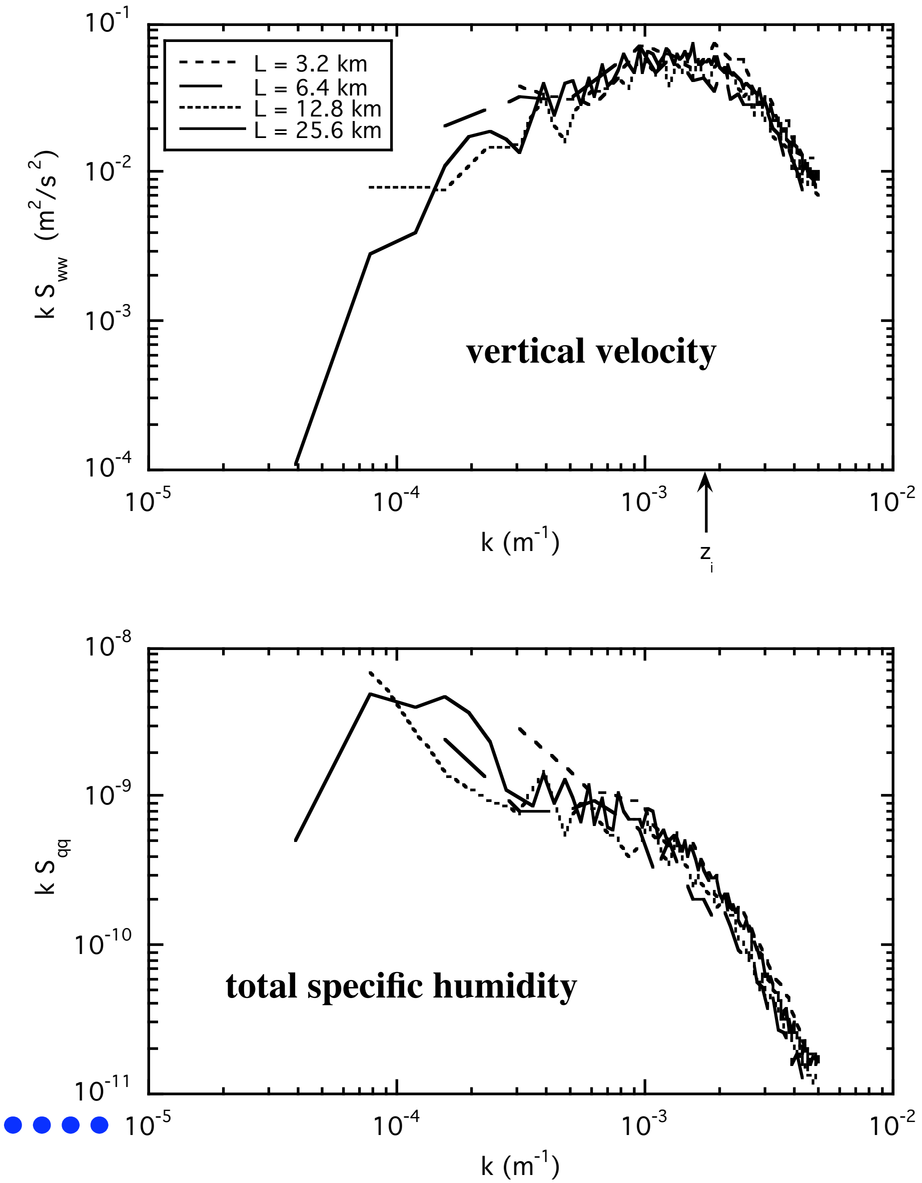
Grant&Brown QJRMS 1999

$$M(q_t^{cu} - \overline{q}_t)\frac{\partial \overline{q}_t}{\partial z} \cong \frac{w_*^{cu}}{l_{cloud}}\overline{q_t'^2}$$

Final Result: $\overline{q_t'^2} \cong \dfrac{M(q_t^{cu} - \overline{q}_t)}{w_*^{cu}} l_{cloud} \dfrac{\partial \overline{q}_t}{\partial z}$

....

LES domain size: How large is large enough?



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Spectra in stratocumulus

- Different domain sizes L